Mustard Cover Crops for Biomass Production and Weed Suppression in the Great Lakes Region

Thomas Björkman,* Carolyn Lowry, Joseph W. Shail, Jr., Daniel C. Brainard, Daniel S. Anderson, and John B. Masiunas

ABSTRACT

Short-season cover cropping can be an important weed management tool. To optimize the use of mustard [*Sinapis alba* L. and *Brassica juncea* (L.) Czern.] in the Great Lakes region, we assessed planting time effects, mustard biomass production, and weed suppression during mustard growth and after incorporation. The study was conducted in Illinois, Michigan, and New York for spring and fall from 2010 to 2012. Mustard was sown every ~10 d from mid-March to early June for spring plantings and from early August to mid-September for fall plantings. Spring mustard biomass, weed density, community composition, and dry biomass were collected at mustard flowering. Fall mustard biomass, weed density, and dry biomass were collected at season end. Spring mustard biomass ranged from <0.5 to 4 t ha^{-1}. Early fall biomass ranged from 3 to 5.5 t ha^{-1}, and was related to growing degree days (GDD) according to a logistic function. Weed biomass during mustard growth was reduced by at least 50% in 9 of 10 site-years (90%) for fall-planted mustard but only 15 of 31 site-years (48%) in spring plantings. Weed suppression was independent of mustard biomass. The total number of weed seedlings emerging after mustard incorporation was not significantly reduced, but there was a species-specific response, with a decrease in common lambsquarters (*Chenopodium album* L.) and grass emergence. The results permit a location-specific recommendation to plant mustard cover crops 13 to 23 August in the southern Great Lakes Region, and no later than 1 to 10 September for adequate biomass production.

Short season cover crops can be used in crop rotations to enhance soil conservation, improve soil health, and inhibit weed populations (Creamer and Baldwin, 2000; Snapp et al., 2005). Cover crops can fill fallow periods between cash crops that might otherwise be vulnerable to erosion or weed establishment. Examples of fallow periods within rotations include late summer following harvest of wheat (*Triticum aestivum* L.) or early season vegetables, such as pea (*Pisum sativum* L.), garlic (*Allium sativum* L.), or onion (*A. cepa* L.). Short season cover crops may also be utilized in spring before late-planted crops. Ideally, short season cover crops should establish quickly to suppress weeds and prevent weed seed rain (Björkman and Shail, 2013), disrupt pest life cycles, protect the soil from extreme rain and wind events (Quinton et al., 1997), reduce soil erosion, scavenge soil N (Thorup-Kristensen, 2001) and increase soil organic matter (Snapp et al., 2005).

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Mustards generally perform best in cool growing conditions and are a potentially valuable cover crop in open niches in early spring or fall in temperate climates. Furthermore, no spring management of cover crops is necessary when the cover crops freeze during the winter. These benefits are only obtained if the planting date is well coordinated with the local climate.

Mustards are most widely known for their capacity to serve as a biofumigant for suppression of crop pests following incorporation into the soil. Mustard plants contain glucosinolates that are hydrolyzed by the enzyme myrosinase to form isothiocyanates (ITCs) (Brown and Morra, 1996). The ITC compounds have the potential to be toxic to a variety of soilborne plant pests, including weeds (Haramoto and Gallandt, 2004), nematodes (Mojtahedi et al., 1993), insects (Blau et al., 1978; Williams et al., 1993), and diseases (Angus et al., 1994; Brown and Morra, 1997).

Mustard cover crops can suppress weeds through a variety of mechanisms both during growth and post-termination. During cover crop growth, weed germination may be inhibited through shade-induced reduction in the ratio of red to far-red light, while subsequent growth and reproduction may be suppressed through competition for light, water, or nutrients (Holt, 1995). Mustard cover crop residues also contain ITCs (Petersen et al., 2001), which can inhibit germination and growth of weeds (Teasdale and Taylorson, 1986). Although not studied extensively in mustard species, other cover crops suppress weeds following incorporation through changes in soil N dynamics, or shifts in pathogens of weeds (Kumar et al., 2008; Mohler et al., 2012).

Abbreviations: GDD, growing degree days. ITC, isothiocyanate.

Mustard cover crop residues reduced emergence and growth of certain weed species in both the greenhouse and field (Boydston and Hang, 1995; Al-Khatib et al., 1997; Krishnan et al., 1998; Stivers-Young, 1998; Haramoto and Gallandt, 2004; Kumar et al., 2009). For example, aqueous extracts of wild radish (*Raphanus raphanistrum* L.) were shown to suppress emergence of sicklepod (*Senna obtusifolia* L.) and prickly sida (*Sida spinosa* L.), but not yellow nutsedge (*Cyperus esculentus* L.) (Norsworthy, 2003). Mustard species differ in their glucosinolate contents, which produce different forms of ITCs. Norsworthy and Meehan (2005) evaluated the ability of ITCs to differentially suppress Texas panicum (*Panicum texanum* Buckl.), large crabgrass (*Digitaria sanguinalis* L.), and sicklepod, and found that weed species greatly differed in their susceptibility to varying ITCs. Yellow mustard was more effective at suppressing shepherd's purse (*Capsella bursa-pastoris* L.), kochia (*Kochia scoparia* L.), and green foxtail (*Setaria viridis* L.) compared to rapeseed (*Brassica napus* L.) (Al-Khatib et al., 1997). Al-Khatib et al. (1997) found that suppression was positively correlated with seed size, with smaller seeds more susceptible to weed suppression compared to larger seeds.

Among mustard cover crops, yellow mustard is readily available, inexpensive, and has potential weed-suppressive properties due in part to high glucosinolate content (Haramoto and Gallandt, 2005b; Kumar et al., 2009). Kumar et al. (2009) found that yellow mustard reduced biomass and seed production of hairy galinsoga [*Galinsoga ciliata* (Raf.) S.F. Blake] by more than 95%, and that following yellow mustard incorporation, hairy galinsoga emergence and biomass accumulation were reduced by more than 50% compared to bare soil. Previous studies have demonstrated suppression of weed biomass and seed production during yellow mustard growth ranging from 51 to 99% (De Haan et al., 1994; Brennan and Smith, 2005; Kumar et al., 2009). However, limited information is available on how yellow mustard growth and weed suppressive ability varies with planting date, or in organic cropping systems.

The various potential benefits of mustard cover crops have not been consistently realized in field settings. For example, mustard cover crops that were aggressively marketed in the central coast of California for biofumigation to suppress soilborne diseases of lettuce (*Lactuca sativa* L.) were found to be largely ineffective (Bensen et al., 2009; Brennan and Boyd, 2012). Several environmental factors may limit the performance of mustard cover crops. Inadequate soil fertility and moisture, as well as insect pests such as flea beetles (*Phyllotreta* spp.), may limit mustard growth, biomass production, and glucosinolate production (Gustine and Jung, 1985; Brown and Morra, 1997). Additionally, sufficient soil moisture post-incorporation is required for biofumigation to be effective (Morra and Kirkegaard, 2002).

To ensure growers can make the most effective decisions about the costs and benefits of utilizing mustard cover crops, more information is needed about flexibility in timing of planting and termination, and how planting time affects mustard biomass production. Vigorous growth and biomass production is essential to obtain the maximum benefit provided by mustard cover crops. Early-season dry matter production by cover crops including mustards is a good indicator of their ability to suppress both weed biomass and seed production, as well as to protect soil from erosion (Quinton et al., 1997; Brennan and Smith, 2005). When growth duration is limited to a short window between cash crops, biomass production may be insufficient. The ideal planting time for mustard cover crops can occur during busy times of the growing season, so the consequences of postponing planting need to be understood so that growers can prioritize accurately. Mustard growth may also be limited by GDD accumulation in cooler years or late planting.

Because ecosystem services provided by cover crops are often dependent on biomass production, thermal time models may be a useful tool in predicting cover crop biomass and phenology based on environmental conditions. Growing degree days are a commonly used predictor in phenological models because plant developmental rate is closely linked with temperature and accumulated heat units (Mirsky et al., 2009; Brennan and Boyd, 2012; Björkman and Shail, 2013). Using 8 yr of data in California, Brennan and Boyd (2012) found a close relationship between accumulated GDD and the biomass of a mustard cover crop mixture. Björkman and Shail (2013) found that GDD models were useful to predict the capacity of buckwheat (*Fagopyrum esculentum* Moench) to suppress weeds. Mirsky et al. (2009) found cereal rye (*Secale cereale* L.) phenological stage could be adequately predicted with GDD, which improved prediction capacity for determining the timing for effective termination using a roller crimper. In order for growers to determine whether a cover crop can fit between cash crops in their rotation niches, they need to know whether it will grow enough in the available time. This information can also aid in the development of more regionally and environmentally specific cover crop selection tools.

To provide the most effective information to farmers about the environmental conditions and length of time required for successful cover crop integration into a crop rotation, cover crop growth must be evaluated under multiple sites and environments. Therefore, yellow mustard cover crop growth was evaluated over 2 yr in fall and 3 yr in spring, at three different sites within the Great Lakes region.

The primary objectives of this study were to: (i) evaluate the effect of yellow mustard planting date in both fall and spring on biomass and weed suppression; (ii) assess the ability of GDD to predict mustard biomass; and (iii) determine optimal planting windows across the Great Lakes region using historic climate data. A secondary objective was to assess whether high and low glucosinolate mustard varieties differed in their ability to suppress weeds following incorporation.

METHODS

Site Description

In spring, the study was conducted at three field locations (Illinois, New York, and Michigan) over 3 yr, 2010, 2011, and 2012. The sites were chosen to represent typical climates across the southern Great Lakes, and fields that are desirable for organic vegetable production. Field locations are described in Table 1. Temperature and rainfall conditions are described in Fig. 1. Locations were selected to represent a range of climates and soils relevant to organic vegetable production in the Great Lakes region. In fall, the study was conducted at two field locations (New York and Michigan) over 3 yr, 2010, 2011, and 2012. Field locations are described in Table 2. Temperature and rainfall conditions are described in Fig. 2.

Treatment and Experimental Design

Spring. Experimental factors included presence or absence of mustard, mustard variety, and planting date. At each site and year, plots were arranged with planting date and mustard variety as

Table 1. Trial descriptions for spring-planted mustards.

Characteristic	Illinois	Michigan	New York
Field location	Cruse Tract Irrigated Vegetable Research Farm, Champaign, IL (40°4′ N, 88°12′ W).	Kellogg Biological Station, Hickory Corners, MI (42°24′ N, 85°23′ W)	Homer C. Thompson Vegetable Research Farm, Freeville, NY (42°31′ N, 76°20′ W)
Number of years managed Organically at start of experiment	First year	2 in 2010 7 in 2011(OCIA† certified since 2007)	6 (NOFA-NY† certified since 2006)
Soil description	Flanagan silt loam (fine Montmorillonitic, mesic Aquic Agridoll)	Kalamazoo sandy loam (fine-loamy, mixed, semi-active, mesic Typic Hapludalf) and Oshtemo sandy loam (coarse-loamy, mixed, active, mesic Typic Hapludalf)	Howard gravelly loam (loamy-skeletal, mixed, active, mesic Glossic Hapludalf)
Previous crop			
2010	Sweet corn	No-till soybean and rye cover crop	Rye cover crop
2011	Soybean	Rye cover crop	Broccoli and rye cover crop
2012	Cucumber	nd‡	Sweet corn
Mustard variety			
2010	Florida Broadleaf and Pacific Gold	Ida Gold and Tilney	Ida Gold and Tilney
2011	Florida Broadleaf, Ida Gold, and Pacific Gold	Ida Gold and Tilney	Ida Gold and Tilney
2012	Ida Gold	Ida Gold and Tilney	Ida Gold and Tilney
Planting dates	15 Mar.	26 Mar.	5 Apr.
	26 Mar.	12 Apr.	15 Apr.
	15 Apr.	29 Apr.	29 Apr.
		6 May	11 May
		20 May	21 May
2011	6 Apr.	31 Mar.	15 Apr.
	14 Apr.	3 May	29 Apr.
	11 May	11 May	6 May
	20 May	18 May	13 May
		31 May	23 May
2012	24 Apr.	nd	3 Apr.
	4 May		13 Apr.
	14 May		30 Apr.
	29 May		7 May
	5 June		18 May

† OCIA: Organic Crop Improvement Association, NOFA-NY: Northeast Organic Farming Association of New York.
‡ nd: not done.

main plots. A no-mustard weedy subplot was randomly assigned to one end of each plot.

Mustard varieties having high or low glucosinolate content were compared. IdaGold (*S. alba*; McKay Seed Co., Moses Lake, WA) and Pacific Gold (*B. juncea*; McKay) are high-glucosinolate varieties (leaf glucosinolate content of 45–50 mmol kg^{-1}; Antonious et al., 2009), Florida Broadleaf (*B. juncea*; Ball Horticultural Co., Chicago, IL) is intermediate (25 mmol kg^{-1}; Charron and Sams, 1999), and Tilney (*S. alba;* MinnDak Growers, Grand Forks, ND) a low-glucosinolate variety (5 mmol kg^{-1}; Thruppoyil, 2011). IdaGold and PacificGold were developed as condiment mustards but are marketed as cover crops. Tilney is a widely grown condiment mustard. Florida broadleaf is a commonly grown vegetable mustard. Mustard was planted up to five times each spring in each location. Target planting dates were set in advance, but adjusted to optimize planting conditions. Depending on year and location, planting dates ranged from the earliest time that the ground was anticipated to be tillable in the spring (~15 March) until the latest time a spring cover crop would be expected to be beneficial (~1 June) (Table 1).

Individual plot sizes were adjusted according to field availability and equipment and ranged from 1.5 (New York) or 3 (Michigan and Illinois) m wide and 9.1 (New York) or 12.2 (Michigan and Illinois) m long. The unplanted no-mustard subplot was 1.5 m long. There were four replications.

Fall. Experimental factors included presence or absence of mustard and planting date. At each site and year, plots were arranged in a randomized block design of planting date with adjacent 3-m no-mustard strips between plots. Mustard was sown approximately every 10 d from 1 August to 16 September, depending on year and location, a range that preliminary trials had shown to include the latest potentially effective date for mustard growth as a cover crop. Individual plots were 1.5 by 7.6 m in New York and 1.8 by 27.4 m in Michigan.

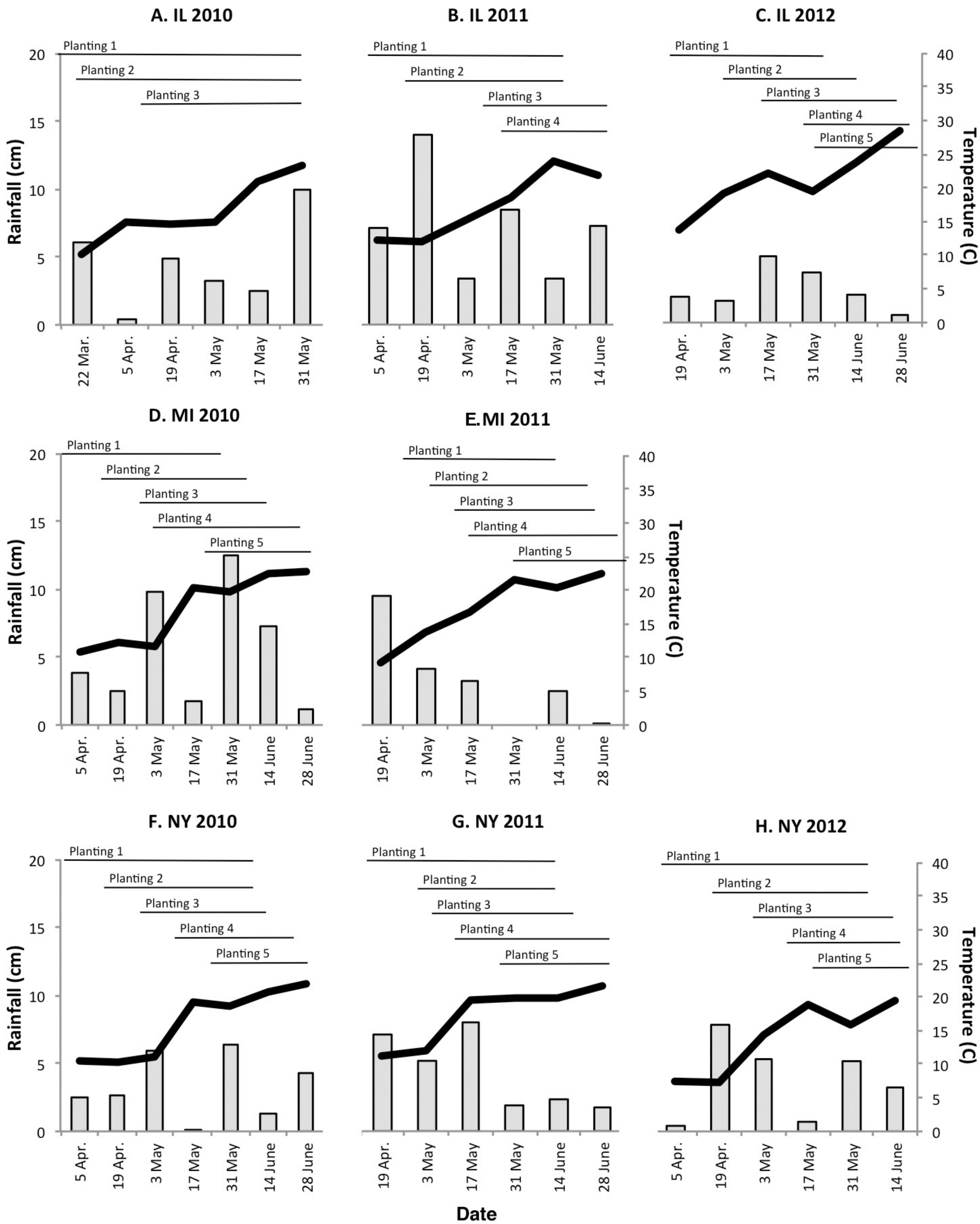


Fig. 1. Mean temperature (line) and total rainfall (bars) during 2-wk intervals for spring-planted mustard trials in (A–C) Illinois (IL), (D–E) Michigan (MI), and (F–G) New York (NY). Dates correspond to the first day of the 2-wk interval. Sowing and harvest dates for each planting are indicated with solid lines at top of each figure.

Table 2. Trial descriptions for fall-planted mustards.

Characteristic	Michigan	New York
Field location	Michigan State University Horticulture Teaching and Research Center, Holt, MI (42°40′ N, 84°29′ W)	Homer C. Thompson Vegetable Research Farm, Freeville, NY (42°31′ N, 76°20′ W)
Number of years managed Organically at start of experiment	3	10 (Certified Organic since 2004)
Soil description	Spinks loamy sand (sandy, mixed, mesic Lamellic Hapludalf)	Howard gravelly loam (loamy-skeletal, mixed, active, mesic Glossic Hapludalf)
Previous crop		
2010	nd†	Pepper
2011	Cultivated fallow	Snap bean
2012	Cultivated fallow	ND
Mustard variety	Tilney	Ida Gold
Planting dates		
2010	nd	11 Aug.
		18 Aug.
		26 Aug.
		2 Sept.
		13 Sept.
2011	4 Aug.	9 Aug.
	16 Aug.	17 Aug.
	23 Aug.	25 Aug.
	1 Sept.	12 Sept.
	9 Sept.	16 Sept.
2012	1 Aug.	nd
	8 Aug.	
	15 Aug.	
	22 Aug.	
	5 Sept.	

† nd: not done.

Field Management and Data Collection

Spring. Fields were plowed, disked, and harrowed as appropriate to soil conditions before the first planting each year. For subsequent plating dates, plots were harrowed immediately before planting to prepare the seedbed and kill weed seedlings. Mustard was sown at 10 kg ha^{-1} using a grass seeder (New York) or grain drill (Illinois and Michigan) with packing wheels to ensure good soil contact. Mustard was terminated at or soon after flowering with a flail mower followed by disking (New York and Illinois) or rotary tilling (Michigan). Field management followed National Organic production requirements (7CFR205.200-206). Mustard dry biomass was collected from a 0.25 m^2 sample area from a random location within the plot. Mustard was dried in an oven at 70°C until a stable weight was obtained, and then weighed. At the end of mustard growth, weed numbers were determined separately in several classes: three dominant broadleaf species, all other broadleaf weeds, and grasses at (Illinois and New York) or before (Michigan) mustard termination. The sample area was 0.25 or 1 m^2 sample area, with the smaller used if weed counts were >400 m^{-2}. Weed dry biomass was measured in a 1 m^2 sample area within both the mustard and no-mustard parts of each plot by cutting at ground level and drying at 60°C. Weed growth was also assessed 3 wk following mustard incorporation. Weed seedlings were counted by species in a 0.5 or 1 m^2 sample area from a random location in the plot as well as in the no mustard subplot.

Fall. Fields were prepared for planting as in spring above. Mustard was sown and terminated as in spring above. Field management followed National Organic standards.

Mustard dry biomass, weed count, and weed biomass were collected at end of season, bloom, or hard freeze (Fig. 2). Mustard biomass was sampled in a 1 m^2 quadrat. Weeds were counted by species in a 1 m^2 quadrat in cover crop plots and in unplantedsubplots. Total weed biomass was collected from the same area as the mustard sample (New York). Biomass samples were dried at 60°C until they reached constant weight, and then weighed.

Statistical Analysis

All statistics were performed using JMP Pro 11 (SAS Institute, Cary, NC).

Spring

The relationship between planting date and biomass was analyzed by calculating the coefficient of determination between the Julian date and the biomass independently for each location. The relationship between GDD and mustard biomass was analyzed as a simple linear regression. Weed density data were log-transformed

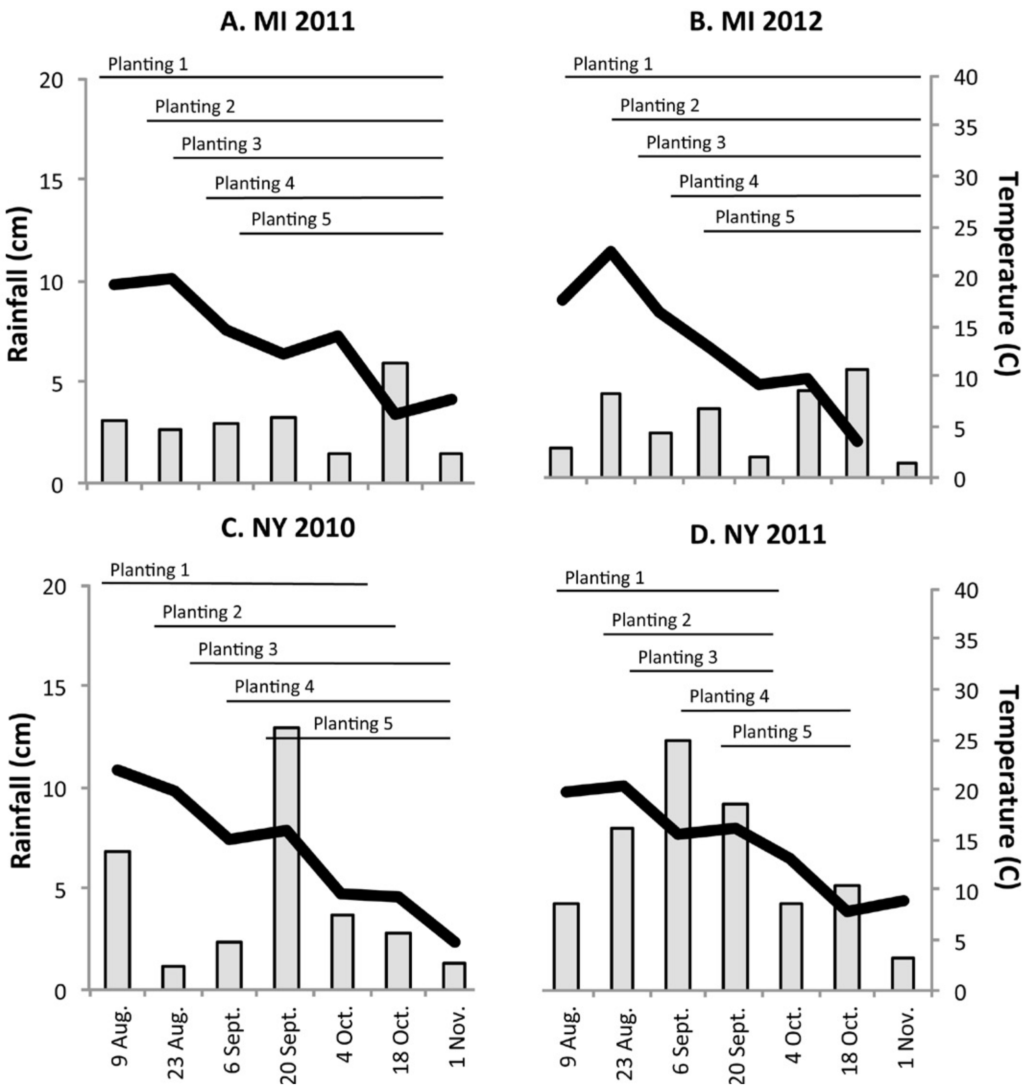


Fig. 2. Mean temperature (line) and total rainfall (bars) during 2-wk intervals for fall mustard trials in (A–B) MI and (C–D) NY. Dates correspond to the first day of the 2-wk interval. Sowing and harvest dates for each planting are indicated with solid lines at top of each figure.

for normalization, the mean and standard error were calculated, and the untransformed values were reported in the figures. Weed reduction was calculated by dividing the density or biomass of weeds in the mustard plot (total or individual species) by the density or biomass in the no mustard subplot after adding a continuity correction factor of 0.5 plant or 1 g m^{-2} to each value. The quotient was log transformed, and these values were analyzed as a General Linear Model with state and mustard variety as predictors.

Fall

Mustard and weed biomass mean and standard error were calculated for each sowing date. The relationship between growing degree days and mustard biomass was fit as a logistic curve. The fit was $Y = Y_{max} + \{(Y_{min} - Y_{max})/[1 + \exp^{\beta(GDD-\alpha)}]\}$ where Y is the mustard biomass at harvest, Y_{min} and Y_{max} are the minimum and maximum biomass estimates, α is the number of growing degree days at 50% of maximum biomass, and β is the steepness of the curve. The fit was calculated using JMP's Nonlinear Regression platform. The relationship from the fall curve was used to predict the mean date on which 935 $GDD_{0°C}$ remain in the season before a killing frost (–4.4°C), with the critical value chosen to represent the inflection point on the curve. The calculation was performed for 3200 weather stations using weather records from 1981 to 2010. The date for an 80% likelihood of reaching the minimum is of greater interest to growers, but that data set was not available from enough stations to generate a map. Therefore we did the calculation for four stations across the region (Duluth, MN; Madison, WI; Grand Rapids, MI; Indianapolis, IN) that had no missing values from 1981 to 2013. The 80% likelihood of accumulating 935 $GDD_{0°C}$ occurred 6, 7, 3, and 7 d, respectively, before the mean date (50% likelihood). The relative weed biomass was analyzed as for spring.

RESULTS

Weather

Temperature. With three sites and 3 yr, we intended to capture a good representation of the weather variation growers in the Great Lakes region might experience. Mean 2-wk temperatures followed the expected pattern, gradually increasing in the spring (Fig. 1) and gradually decreasing in the fall (Fig. 2). For spring plantings, initial temperatures increased from 10 to 15°C for early plantings to 20 to 30°C for later plantings. For spring plantings, Illinois had the warmest temperatures and reached 10°C 2 to 3 wk sooner than Michigan and New York (Fig. 1). In the fall, mean 2-wk

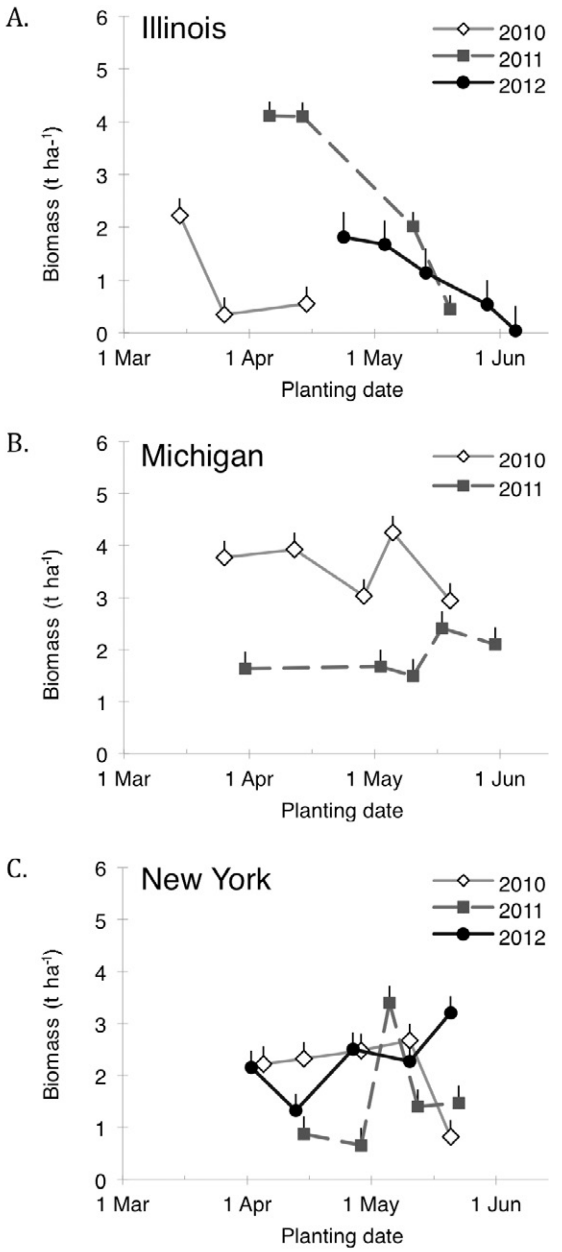


Fig. 3. Spring planting date effect on mustard dry biomass accumulation at termination at three sites in the Great Lakes region. Mustard varieties are listed in Table 1. Weather conditions are in Fig. 1. Bars are the standard error of the mean of four replicates.

temperatures declined from approximately 20 to 25°C for early plantings to 2 to 10°C for later plantings.

Rainfall. Mean 2-wk rainfall totals ranged from approximately 0 to 15 cm (Fig. 1 and 2). For spring-planted mustard, extended dry periods coupled with warm temperatures were most evident in Illinois in 2012, and for New York and Michigan in 2011 (Fig. 1). In contrast, early spring of 2011 was excessively wet in all three locations (Fig. 1). For fall plantings, extended dry periods occurred for early plantings in Michigan, but not New York (Fig. 2). Fields typically have water-saturated soil following snow melt in the spring. Crop water needs are met when rainfall is about 5 cm in each 2-wk period. We observed that periods with higher rainfall also had sheet erosion disturbing seedlings, waterlogging, and hypoxic inhibition of roots and seeds.

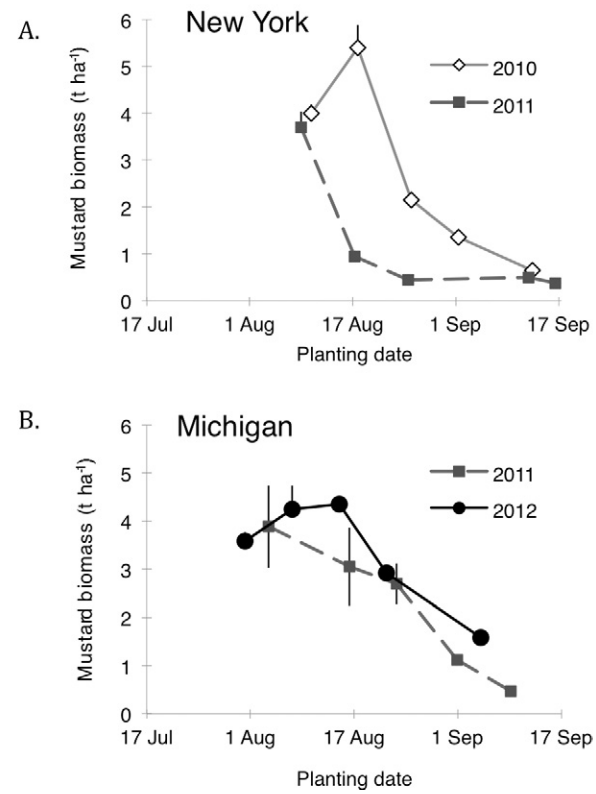


Fig. 4. Fall planting date effect on mustard dry biomass accumulation by killing frost. Bars are the standard error (SE); when bars are not visible, the SE was smaller than the symbol.

Mustard Biomass

Mustard establishment was more difficult in spring (Fig. 3) than in fall (Fig. 4).

Spring Plantings. We sought to determine the window for successfully establishing mustard cover crops in the springtime by making sequential plantings from the time the ground could first be worked until typical summer heat arrived in early June. In Illinois, although higher growth occurred at the earliest planting dates, the relationship was weak (r^2 = 25%); in New York (r^2 = 0.1%) and Michigan (r^2 = 8%), there was no consistent relationship between mustard biomass and planting date (Fig. 3).

Mustard did not establish consistently in the spring. In each location, mustard biomass was highly variable between years (Fig. 3). Mustard biomass had the greatest variation in Illinois, ranging between <0.5 to 4 t ha^{-1}. In New York, mustard biomass ranged between 1 and 3 t ha^{-1} and in Michigan mustard ranged from 1.5 to 4 t ha^{-1}. Mustard establishment was unsatisfactory on some dates. Of the 40 intended planting dates in our spring trial, mustard was limited to <1 t ha^{-1} 20% of the time. Therefore, ground cover was insufficient to limit weed growth. Due to saturated soil conditions, it was not possible to plant on all planned dates. If temperature was the limiting factor for growth, as might be expected in the spring, then there should be a strong positive relationship between GDD and biomass production. Such a relationship did not exist (Fig. 5A), with a slope of −0.0001 (t ha^{-1})/GDD, $P = 0.26$.

Fall Plantings. Sequential plantings were done in the fall in both Michigan and New York beginning approximately 1 August, simulating when land would be available following the harvest of early vegetable crops, until a few weeks before the

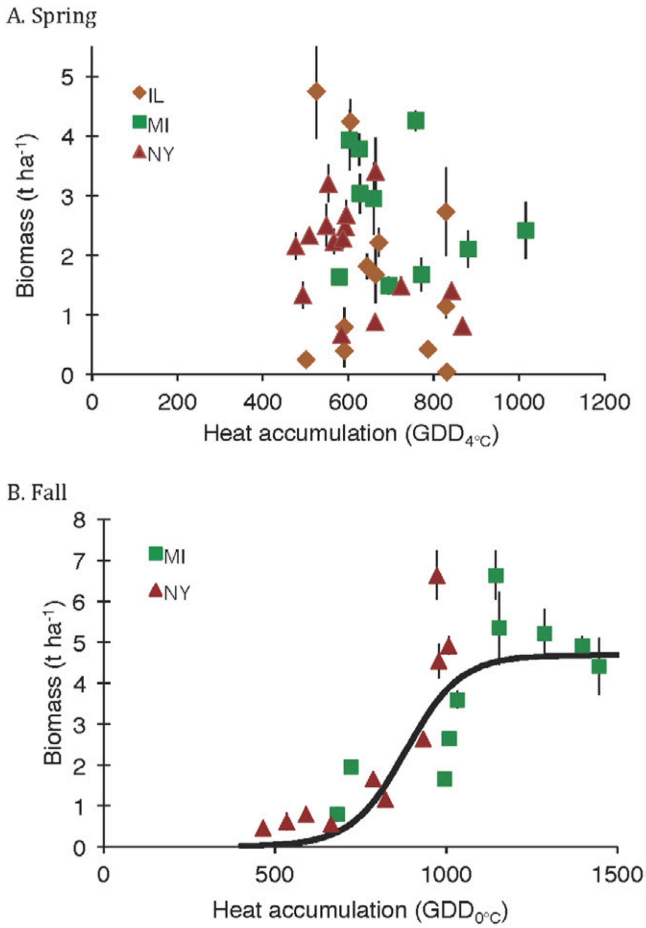


Fig. 5. Relationship between heat accumulation and mustard dry biomass in (A) spring and (B) fall plantings. Points are planting-date means. Bars are the standard error (SE); when bars are not visible, the SE was smaller than the symbol. Growing degree days have a base of 4°C in the spring and 0°C in the fall, with the different bases reflecting crop response to rising and falling temperatures. Spring heat accumulation explained 3% of the variation in biomass (R^2 NS). In fall, biomass followed a logistic fit, reaching a maximum at a heat accumulation of ~1100 growing degree days $(GDD)_{0°C}$.

historical mean first frost. Mustard cover crops grew better in the fall than in the spring and fall mustard growth was greater with earlier planting dates (Fig. 4). Optimal planting time for biomass accumulation at the New York and Michigan sites was in the first half of August, with a rapid decline in growth if planted later. Mustard biomass from early planting dates in the fall ranged from 4 to 5.5 t ha^{-1} in New York and 3.5 to 4.5 t ha^{-1} in Michigan, whereas spring plantings exceeded 4 t ha^{-1} only once among 37 plantings.

In the fall there was a strong relationship between temperature and biomass production (Fig. 5B). Temperature was accumulated using a 0°C base temperature because preliminary experiments have demonstrated that mustard continued to accumulate biomass as long as temperatures were above freezing, and a killing frost had not yet occurred. Little biomass was measured if there were fewer than 600 $GDD_{0°C}$. There was a sharp increase in biomass between 700 and 1000 $GDD_{0°C}$. With additional heat accumulation (>1200 $GDD_{0°C}$), the variation in biomass was caused by other factors.

The fit of mustard biomass as a function of heat accumulation was a logistic curve where

$$\text{Mustard biomass at harvest} = Y_{max} + [(Y_{min} - Y_{max})/1 + \exp^{\beta(GDD - \alpha)}]$$

where Y_{min} and Y_{max} are the minimum and maximum biomass, α is the number of growing degree days at 50% of maximum biomass, and β is the steepness of the curve. The parameters had the following estimates ($\bar{x}$ ± SE): = 3.8 ± 0.2 t ha^{-1}, = 0.4 ± 0.2 t ha^{-1}, α = 884 ± 39 $GDD_{0°C}$, β = 0.007 ± 0.003.

The maximum biomass was reached at 1200 $GDD_{0°C}$, but additional heat accumulation from planting earlier caused other differences that could affect weed growth in fall or the following spring. The plants flowered, and sometimes made seed, before they were killed by frost. Straw from the older plants stood into the winter and sometimes held snow during the winter at times when unplanted ground was snow free.

The predicted latest fall planting date for mustard varies widely across the Great Lakes region (Fig. 6). The map was generated from historical weather records to determine the mean date when 935 $GDD_{0°C}$ accumulated before a killing frost (–4.5°C). Growers may want a more conservative last planting date than a 50% chance of reaching the minimum. We calculated the adjustment to predict an 80% chance of reaching the minimum heat accumulation. That date was estimated for four representative stations (Duluth, MN; Madison, WI; Grand Rapids, MI; Indianapolis, IN). The 80% likelihood of obtaining the minimum heat accumulation occurred 6, 7, 3, and 7 d, respectively, before the mean date (50% likelihood). Thus, a more prudent last planting date would be a week earlier than the model estimate. Much of the southern Great Lakes region, where these cover crops might be particularly popular, fell in the same zone, one with a modeled last planting date of 1 to 9 September. Thus the conservative (8 yr of 10) last planting date is 23 August to 2 September for this region. A further adjustment can be made to find the optimal planting date, which is an additional ~150 $GDD_{0°C}$ earlier, because the biomass reaches its maximum at ~1100 to 1200 GDD, where the model uses 935 (Fig. 5) to find the last date. Given a mean temperature of 19°C in mid-August, the optimum date is 7 to 10 d earlier than the last date. Thus, the target planting date for the region marked 1 to 9 September in Fig. 6 is projected to be 13 to 23 August.

Mustard Weed Suppression

We sought to estimate the potential value of a spring and fall mustard cover crop to suppress weed growth. Weed biomass was measured at the time of mustard incorporation both within the mustard stand and in a mustard-free subplot. Mustard suppression of weed biomass compared to the mustard-free subplot varied considerably by season, site, year, and planting date (Fig. 7 and 8).

Spring Plantings

Spring weed suppression by mustard ranged from 0 to 99%. Greater than 50% suppression of weed biomass occurred in 19 out of 34 mustard plantings (55%). Greater than 90% weed suppression occurred in only 3 of 31 cases (9%). The observed inconsistent weed suppression in spring was not associated with obvious causes. Earlier mustard planting dates in spring (March and April) in Illinois were more effective at suppressing

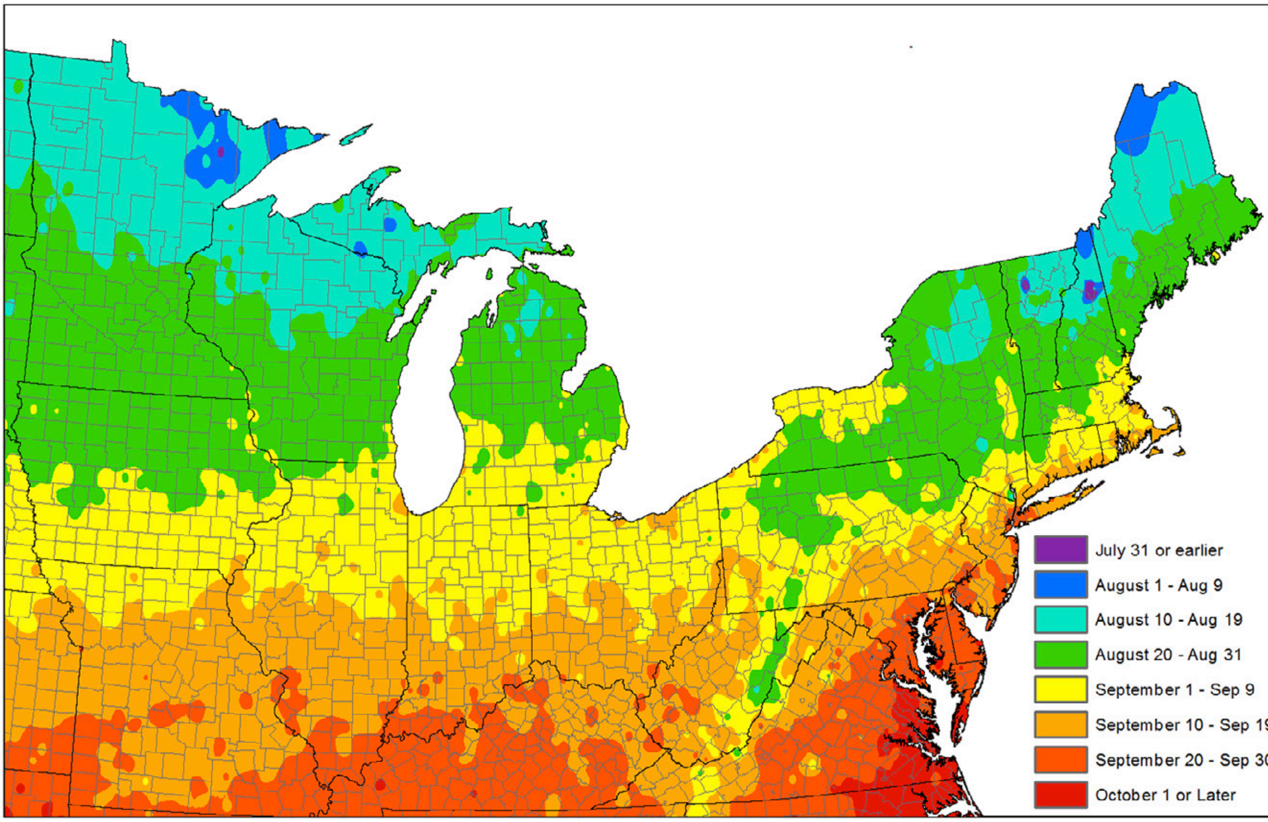


Fig. 6. Predicted last fall planting date for mustard. The mean date for which 935 growing degree days $(GDD)_{0°C}$ will accumulate before a killing frost. The map was produced by the Midwest Regional Climate Center using temperature data at 3200 weather stations between 1981 and 2010. The last date with a four in five chance of meeting the minimum GDD, rather than the 50% used in this figure, is about 1 wk earlier, and maximal biomass is obtained by planting about 1 wk before that date. Thus, the target planting date to obtain a satisfactory mustard cover crop would be about 2 wk earlier than the date on the map.

weeds than later dates. In Michigan 2010 and 2011, mustard biomass effectively suppressed weeds at all but the last planting date in 2010. Suppression was highly variable in New York based on year. In 2010, all mustard planting dates gave effective weed suppression except the last planting date. In 2011, weed suppression was poor at early planting dates, and in 2012 only the middle planting date showed >50% suppression. Weed suppression in the mustard crop was related to mustard biomass only in Illinois (Fig. 9A). The regression equation is ln(weed biomass in mustard/weed biomass in unplanted ground) = $a + b$ (mustard biomass t ha$^{-1)}$. In Illinois, the calculated parameters were $a = -0.41 \pm 0.25$ (ns) and $b = 0.56$ ($\pm$ 0.09) ($P < 0.0001$). The untransformed result is that weed biomass was 66% of the unplanted plots at zero mustard, with a further 43% reduction in weed biomass for each t ha^{-1} of mustard. In Michigan, $a = -1.86 \pm 0.20$ ($P < 0.0001$) and $b = 0.16 \pm 0.7$ ($P = 0.015$), which corresponds to a reduction in weeds to 16% of unplanted ground in mustard, with a slight increase in weed biomass with mustard biomass. In New York, $a = -0.777 \pm 0.18$ ($P < 0.0001$) and $b = 0.03 \pm 0.08$ (ns), meaning that mustard reduced the biomass to 46% of unplanted ground regardless of mustard biomass.

Weed-species-specific responses occurred both for growth in the mustard stand (Table 3) and emergence after incorporation (Table 4). Weed emergence after mustard incorporation reflects the potential weed pressure in subsequent crops. The total number of weed seedlings was not significantly reduced in the mustard compared to no mustard plots, but there was a species-specific response (Table 4). Common lambsquarters and grass emergence were significantly lower following mustard incorporation, but Powell amaranth (*Amaranthus powellii* S. Watson) and hairy galinsoga emergence were higher.

Mustard cover crops both stimulated and decreased weed numbers within the mustard stand. In Illinois, mustards increased the number of grasses, but decreased grass total biomass because they occurred in patches of many small seedlings. In New York, mustard growth suppressed a number of winter annual weed species, including common chickweed (*Stellaria media* L.) and shepherd's purse, but not summer annual species (Table 3). Incorporated mustard biomass decreased emergence of common lambsquarters and grasses, but increased emergence of amaranth species and hairy galinsoga (Table 4). The high-glucosinolate mustard variety (Ida Gold) did not confer additional weed suppression compared to low glucosinolate mustard varieties (Table 4).

Fall Plantings

Fall-planted mustards suppressed weeds more consistently than did spring-planted mustards. In fall mustard plots, weed biomass ranged from 60% greater to 99% less than no-mustard controls (Fig. 8). Suppression of weed biomass by more than 50% occurred in 90% (9 of 10) of cases for fall-planted mustard. Weed suppression was obtained even on late planting dates when mustard was small (~50 g m^{-2} dry biomass) (Fig. 8).

Weed biomass in the mustard stands was substantially lower than in unplanted ground. The amount of weed suppression in the mustard stand was generally not affected by the amount of

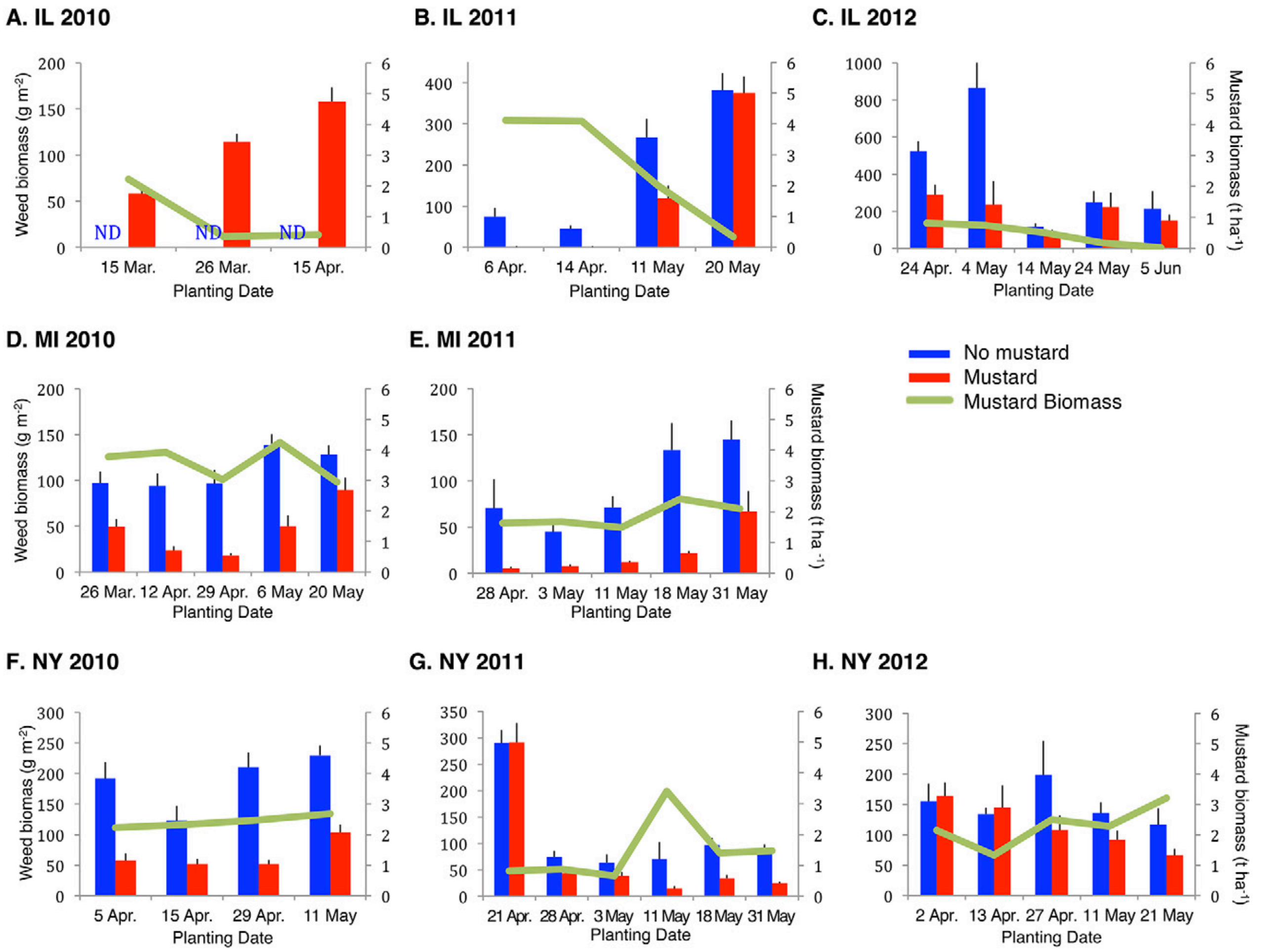


Fig. 7. Weed biomass and weed suppression by mustard in spring following different planting dates. Green lines are mustard biomass as reported in Fig. 3. Biomass was measured at mustard termination on dates shown in Fig 1. The error bars are the standard error of the mean of four replications.

mustard biomass either in the spring (Fig. 9A) or the fall (Fig. 9B). The lack of correlation between mustard biomass and weed suppression was observed in the spring whether the overall weed suppression was great (Michigan, ~70%) or small (New York, ~20%). Substantial suppression was obtained in plots with unusually high mustard biomass in Illinois (>2 t ha^{-1}), but not in the equally productive Michigan plots.

DISCUSSION

Mustard cover crops have the potential to suppress weeds, recycle nutrients, and contribute to soil organic matter (Stivers-Young, 1998; Weinert et al., 2002; Thorup-Kristensen, 1994). In the Great Lakes region, spring typically begins with water-saturated soil after snow melts, and planting opportunities are sporadic as the soil dries. Soil is often too wet for cultivation to be effective in the spring and can result in poor weed control. Mustards can be established in cooler soil compared to other cover crops and are well-suited for a spring planting window before a later-planted vegetable. Fall-sown mustards planted after wheat or spring vegetables provide weed suppression during periods of the growing season during which labor is often limiting. In typical years, fall-planted mustards winterkill, thereby reducing the necessary soil disturbance and labor for an early-planted crop the following year. Compared to oat (*Avena sativa* L.), a commonly used winterkill cover crop, mustard produced similar biomass when planted early in the fall (3 September), but produced 1 to 1.5 t ha^{-1} greater biomass when planted at a later date (16 September) (Stivers-Young, 1998).

We sought to determine the window for successfully establishing mustard cover crops in both the spring and fall throughout the Great Lakes region. Mustard plantings were initiated in the spring when the ground could first be worked and ended with the onset of high summer temperatures (approximately 1 June). In Illinois, the best growth consistently occurred at the first possible planting date, while in New York and Michigan, there was no consistent relationship between mustard biomass and planting date (Fig. 3). This difference is likely due to ~3 to 6°C higher spring and early summer temperatures in Illinois. Variability in mustard biomass was greater between years than between planting dates in Michigan, while in New York, mustard biomass variability was high between planting dates in any given year with no predictable pattern.

Sequential fall plantings started around 1 August and continued until a few weeks before the expected first frost. This period was chosen to simulate when land would be available following the harvest of early crops. Mustard cover crops grew better in the fall than in the spring, particularly in New York. When planted at the optimal date in the fall, mustard biomass was about 4 t ha^{-1}, whereas the typical range from spring plantings was from 2 to 4 t ha^{-1}. While some studies have found a

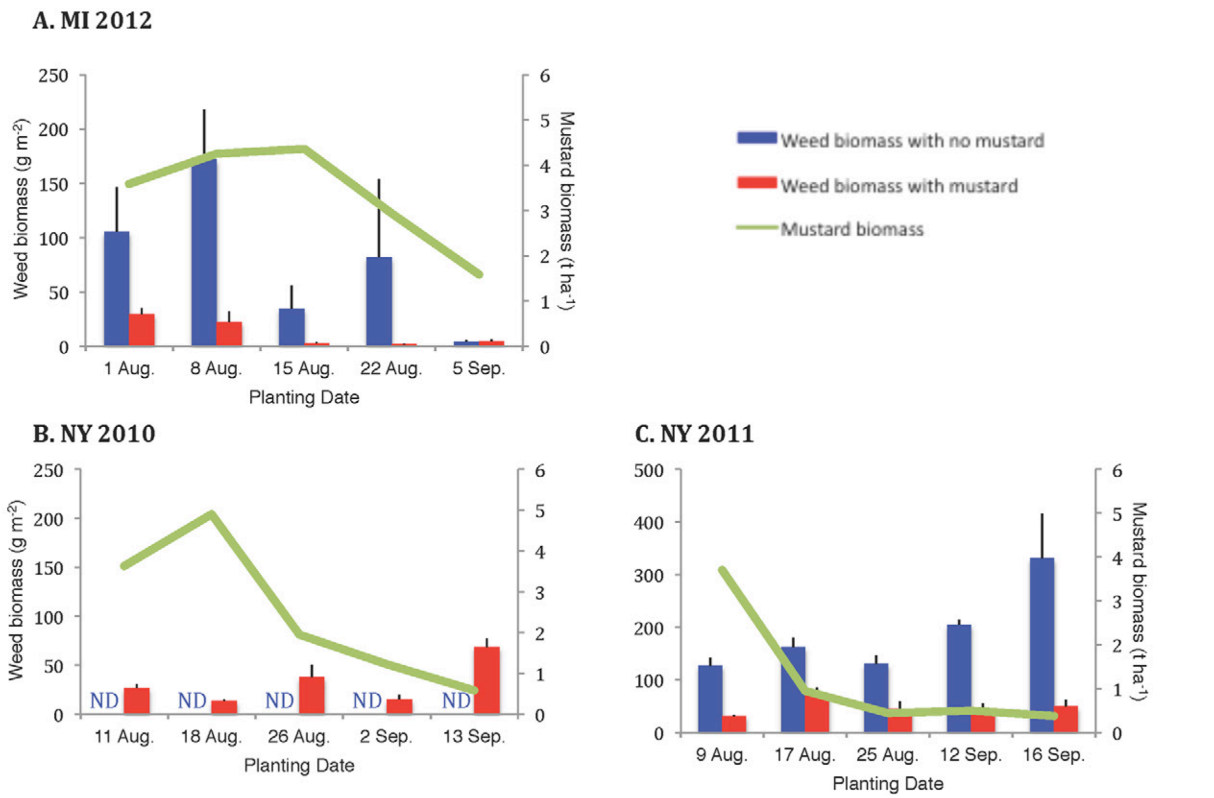


Fig. 8. Weed biomass and weed suppression by mustard in fall following different planting dates. Green lines are mustard biomass as reported in Fig. 4. Biomass was measured at mustard termination on dates shown in Fig. 2. The error bars are the standard error of the mean of four replications. ND = Not Done

similar range in mustard biomass in northcentral and northeastern United States (Stivers-Young, 1998; Haramoto and Gallandt, 2005a; Ackroyd and Ngouajio, 2011), spring mustard biomass has been found to reach as high as 6.8 t ha^{-1} (Kumar et al., 2009). In both New York and Michigan, fall mustard biomass was generally greater with earlier planting dates, largely due to greater GDD accumulation.

In the climate we studied, fall-sown mustard grew well, and it was possible to determine a relatively narrow range of planting dates that produced good growth. Thus we propose a target planting date of 13 to 23 August for the southern Great Lakes. That region is the band in Fig. 6 labeled 1 to 9 September. The recommendation is based on having maximum, rather than adequate, biomass and for obtaining maximum biomass before frost in 8 yr out of 10 rather than 5 yr.

Good growth of mustard was sometimes obtained in the spring. However, the variation pattern of mustard biomass accumulation did not allow a date- or temperature-based prediction of when growers should plant for best success. In Illinois, the warmest site, good growth was associated with sowing as early in the spring as possible. However, planting opportunities at that time will be difficult to predict: one year late March was too late, the following year early April was the soonest the field could be planted.

Causes of Variation in Cover Crop Growth

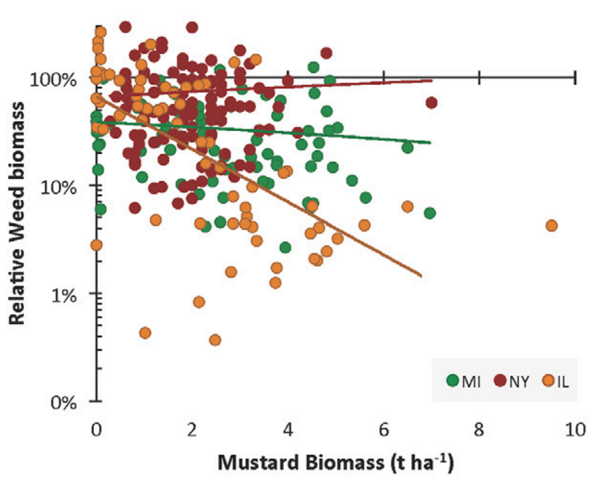
We sought to evaluate whether variation in mustard biomass could be explained by temperature and precipitation. If temperature was the limiting factor for growth, then there should be a strong relationship between GDD and biomass production. The relationship was strong in the fall if there were fewer than ~1200 $GDD_{0°C}$ between planting and frost (Fig. 5B). Timing of frost likely prohibited later-planted mustard from reaching maximum biomass production. The relationship between GDD and mustard biomass did not exist in the spring (Fig. 5A). Therefore, other factors were likely responsible for the variation in spring biomass production.

Once sufficient temperature accumulation was achieved and temperature was no longer growth-limiting, variation in mustard biomass could have been caused by a number of factors. Both Michigan and Illinois, and to a lesser extent New York, had large variability in mustard biomass due to year. Lower mustard biomass in Michigan in spring of 2011 compared to 2010 may have been a result of reduced rainfall and very high temperatures (Fig. 1). Greater precipitation during early growth of the first two mustard planting dates in Illinois in 2011 may have accounted for the twofold increase in biomass. However, no other obvious patterns in weather were found to explain mustard biomass differences between years and planting dates. Based on our observations, other factors leading to variation in mustard biomass included waterlogging from heavy rainfall, premature flowering, insect herbivory, variation in residual fertility, and greater duration of growth.

Mustard Weed Suppression Was Inconsistent

Our results demonstrate that mustard cover crops have potential value in suppressing weed growth, but that suppressive ability varied with location, year, and planting date (Fig. 7 and 8). In general, fall mustard was more effective at suppressing weed growth than spring mustard; suppression of weed biomass by more than 50% occurred in 90% (9 of 10) of cases for fall-planted mustard compared to only 56% (15 of 31) of cases

A. Spring



B. Fall

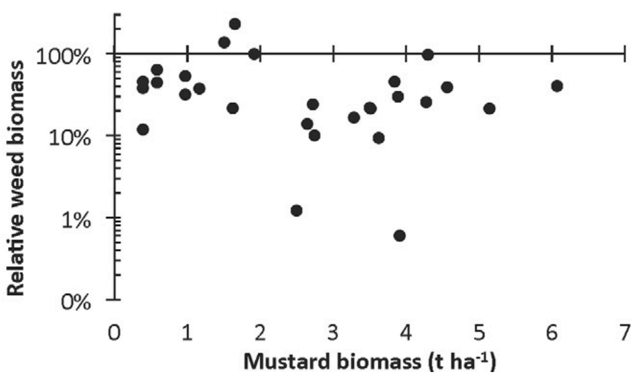


Fig. 9. Effect of mustard biomass on weed suppression within the mustard stand in (A) spring and (B) fall plantings. Spring data are from three states; fall data are from 2 yr in New York (NY). Weed biomass reduction is shown, and was analyzed, on a log scale of weed biomass relative to that on paired plots without mustard. Lines in A are regression lines in which the slope is non-significant for NY and Michigan (MI); in Illinois (IL) weed biomass was reduced by 43% for each t ha^{-1} of mustard.

for spring-planted mustard. Furthermore, spring-planted mustard failed to provide any detectable weed suppression in 21% (7 of 34) of cases. A 50% reduction in weed biomass is a generous criterion; growers who use cover crops for weed suppression would expect substantially less weed growth in their cover crops. Previous studies have documented suppression of weed biomass during yellow mustard growth of 51 to 99% depending on duration of interference, year, and weed species (DeHaan et al., 1994; Brennan and Smith 2005; Kumar et al., 2009).

In several specific cases, variation in weed suppression in our study appeared to be best explained by differences in mustard establishment and growth. For example, in 2011 and 2012 in Illinois, early spring-planted mustards suppressed weeds well, but mustard planted after mid-May failed to provide adequate suppression (Fig. 7B–7E and 9A), due in part to poor mustard growth (<0.5 t ha^{-1}). However, our results demonstrate that in general, mustard biomass was a poor predictor of weed suppression when all site-years were analyzed (Fig. 9A and 9B). Only in Illinois did greater mustard growth (>2 t ha^{-1}) suppress weeds better. In Michigan, greater biomass did not suppress weeds better. The Michigan result would be obtained if favorable conditions stimulate both mustard and weed growth. Moreover, high mustard biomass production was rarely obtained in spring plantings because growing conditions were not conducive. In fall, weed suppression was obtained even with late planting dates in which the mustard was small (Fig. 8); that result is not expected if competition for light and water is the primary suppression mechanism. In other cases, mustard and weed biomass appeared to be positively correlated, presumably because environmental conditions that reduced mustard growth, such as suboptimal N or moisture, also reduced weed growth.

Suppression of weeds during mustard growth was also influenced by variations in weed community composition coupled with differences in the response of weed species to mustard interference. As with previous studies, we observed variation in the density and composition of weed species across planting dates and site-years, likely due to differences in edaphic conditions, as well as the dormancy status and vertical distribution of seeds in the weed seedbank (Cousens and Mortimer 1995; Grundy, 2003). Because mustard suppressed some weed species more effectively than others (Table 3), differences in weed communities may help explain the lack of a consistent relationship between mustard biomass and weed suppression. Variation in community composition may partially explain the higher density of grasses within mustard stands in Illinois (249%), however, mustards still resulted in lower weed biomass. In two other studies, Florida Broadleaf and Southern Giant mustard stimulated grass emergence (P > 90%) (Masiunas, unpublished data, 1998 and 2003). In general, mustard suppressed the biomass of low-growing winter annual species including shepherd's purse and chickweed more effectively than summer annual species like Powell amaranth (Table 3). Variation in the suppressive ability of cover crops was also observed by Kruidhof et al. (2008), who attributed relatively weak suppression of common vetch (*Vicia sativa* L.) to its more sensitive shade-avoidance response. Strong shade-avoidance responses have been documented for several weed species in our study including Powell amaranth (Brainard et al., 2005) and common lambsquarters (Causin and Wulff, 2003), and may help explain relatively weak suppression of the biomass of these species by mustard.

The greatest value of mustard cover crops for organic weed management would be if certain weed species were suppressed in the subsequent crop. We tested whether there was a residual suppressive effect of mustard on particular weed species and whether suppression was more pronounced in the high-glucosinolate mustard variety, Ida Gold. Ida Gold mustard is marketed specifically for its biofumigation potential. Ida Gold is high in the glucosinolate sinigrin (40 mmol sinigrin kg^{-1} leaf), whereas Tilney is low (5 mmol sinigrin kg^{-1} leaf). If biofumigation were killing weed seeds or seedlings (Brown and Morra, 1996, Norsworthy et al., 2005) there would be a significant difference between the two mustard varieties. Contrary to expectation, no weed species differed significantly in emergence between the two varieties (Table 4), and the overall difference was under 2%. Therefore, biofumigation can be rejected as a mechanism for affecting weed emergence following mustard under the current conditions.

Several explanations may account for the apparent lack of a biofumigation effect in this study. First, glucosinolate content of the mustards may have been too low to induce suppression. The high-glucosinolate mustard, Ida Gold, typically contains sinigrin at 40 mmol kg^{-1} and when producing 3×10^6 g ha^{-1} dry biomass has

Table 3. Suppression of individual weed species in spring-planted mustard stands. Results were pooled for 3 yr and 5 plantings per year.

Weed	State	Plots†	Relative weed abundance (mustard vs. no mustard)‡
		Population	
Shepherd's purse	NY	120	62%
Common lambsquarters	IL	68	116%
	MI	38	59%*
	NY	120	120%§
Common chickweed	NY	120	81%§
Powell amaranth	IL	68	71%§
	MI	18	15%***
	NY	120	98%
Grass	IL	91	249%***
	MI	40	80%
	NY	120	82%
		Biomass	
Shepherd's purse	NY	120	47%***
Common lambsquarters	NY	120	75%
Common chickweed	NY	120	42%***
Powell amaranth	NY	120	103%
Grass	NY	120	72%
	IL	20	69%*

* Significant at $P \leq 0.05$.

*** Significant at $P \leq 0.001$.

† Plots in which weed occurred at > 10 m^{-2} within the unplanted no-mustard subplot.

‡ Number or biomass of weed seedlings relative to no-mustard subplot in the mustard stand at mustard termination. Effect calculated using analysis of variance of log-transformed values.

§ Significant at $P < 0.1$.

the potential, with perfect conversion, to produce 120 mol ha^{-1} of methyl isothiocyanate (Morra and Kirkegaard, 2002). Norsworthy et al. (2005) found a large amount of variability in the glucosinolate content of mustard species bred specifically for biofumigation potential, with total glucosinolate content ranging from 86 to 267 mol ha^{-1}. The fumigant Vapam (Amvac Chemical Corporation, Los Angeles, CA), whose active ingredient is methyl dithiocarbamate, produces 3900 mol ha^{-1} of methyl isothiocyanate at the recommended application rate of 700 L ha^{-1}. Thus even the highest glucosinolate potential of the mustards in our trial represented only ~3% of recommended fumigant rate.

Surprisingly, mustard residues suppressed emergence for only two weed species, and actually stimulated emergence of both *Amaranthus* species and hairy galinsoga (Table 4). This result is contrary to what Kumar et al. (2009) found, that mustards suppressed hairy galinsoga emergence by 53 to 62% even without rapid incorporation or plastic mulch. One potential explanation is that environmental conditions in our trial resulted in low glucosinolate and isothiocyanate concentrations that were stimulatory. Norsworthy and Meehan (2005) found that under greenhouse conditions, low isothiocyanates stimulated weed emergence. Alternatively, N released from decomposing mustard residue may have stimulated emergence. This explanation is especially plausible for Powell amaranth, for which germination is stimulated by N fertilization (Brainard et al., 2006). However, if N release were significant, increased emergence of other nitrophilic species, such as lambsquarters (Bouwmeester and Karssen, 1993) would also be expected. Interactions with fungal pathogens are another

Table 4. Effect of cover crop treatment on the reduction of weed emergence following spring-planted mustard incorporation. Weed emergence was assessed for the first flush of weeds, 3 wk after incorporation. The number of weed seedlings, or their biomass, was log transformed and the difference tested statistically. The back transformed values represent the weed population or biomass relative to the no-mustard control.

		Relative weed abundance‡	
Weed	Trial†	Mustard vs. no mustard	High vs. low glucosinolate
Common lambsquarters	NY10, 12 MI11	46%***	115%
Powell amaranth	NY10, 12 MI11	214%***	108%
Hairy galinsoga	NY12	466%***	57%
Carpetweed	MI11	96%	89%
Grasses	NY12, MI11	68%**	90%
Total	all	84%	98%

** Significant at $P \leq 0.01$

*** Significant at $P \leq 0.001$

† Plantings in which parameter was measured and weed occurred at >10 m^{-2}

‡ Number of weed seedlings relative to no mustard subplot, or in high-glucosinolate mustard (IdaGold) to low-glucosinolate mustard (Tilney).

mechanism of suppression or stimulation of weed emergence, and can contribute to inconsistent results following cover crop incorporation (Kumar et al., 2008; Mohler et al., 2012).

Implications for Management

If the goal of a mustard cover crop is to obtain maximum biomass production, growers in the Great Lakes region have a short fall planting window following harvest of a previous crop. The latest fall planting date for mustard varied widely across the Great Lakes region, but around the southern shore of these lakes we recommend 13 to 23 August for optimal growth and no later than early September for stands that have management value. Fall-germinating weeds can be suppressed with mustard cover crops.

Spring plantings were sufficiently variable that we conclude this planting window is likely less valuable than fall in the Great Lakes region. Spring plantings have the additional disadvantage of requiring mechanical or chemical suppression before planting subsequent crops. Subsequent crops, including pea, lettuce, and chard (*Beta vulgaris* L.), may also be inhibited by spring planted mustard (Kumar et al., 2009). The poor ability to predict whether a good stand could be anticipated on a particular planting date further reduced the value of mustard as a management tool in this season. There may be exceptions in which the soil is amenable, such as planting only in early spring in the warmest areas in years where the field can be worked. Vegetable growers in this region may be best served if more climate-appropriate spring-management practices are emphasized.

CONCLUSIONS

- Weed suppression, while variable, was obtained even if the mustard plants were small.
- Mustard cover crops grew particularly well in the fall, if sown after summer crop harvests.
- Glucosinolate content was unrelated to weed suppression.
- The optimal planting window for mustard cover crops was short but predictable, occurring in mid-August in the southern Great Lakes.

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