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Buckwheat Species as Summer Cover Crops for Weed Suppression in No-Tillage Vegetable Cropping Systems

Mary T. Saunders Bulan, David E. Stoltenberg, and Joshua L. Posner*

Buckwheat is a broadleaved annual species that is often used as a summer cover crop for its quick growth, weed suppressive ability, and ease of management. Tartary buckwheat is a species related to buckwheat, with many of the same traits valued in buckwheat as a cover crop. However, Tartary buckwheat has been reported to grow more vigorously than buckwheat, especially in cool conditions, which might fill a unique niche for vegetable farmers in Wisconsin and other northcentral states. Our research objectives were to determine the effectiveness of Tartary buckwheat relative to buckwheat for weed suppression, both during the cover-cropping phase and after cover-crop termination during cabbage production, and quantify weed suppression, soil compaction, soil nitrogen availability, and cabbage yield in no-tillage (roller-crimped or sickle-bar mowed) and conventional-tillage (rototilled) systems. Across three site-years, we found that buckwheat emerged earlier and produced 64% more shoot dry biomass than Tartary buckwheat. Pretermination weed shoot biomass (predominantly *Amaranthus* and *Setaria* spp.) in Tartary buckwheat treatments was approximately twice that of buckwheat, and did not differ from weed shoot biomass in a control fallow treatment. Cabbage yield did not differ between cover crop species nor did yield differ between conventional-tillage cover cropped and control fallow treatments. However, weed biomass was greater, and cabbage yield was reduced, in no-tillage compared to conventional-tillage treatments. We also found evidence of greater soil compaction and less nitrate–nitrogen (NO_3–N) availability in no-tillage than conventional-tillage treatments. These results suggest that Tartary buckwheat is not a suitable summer cover crop alternative to buckwheat for weed suppression prior to cabbage production.

Nomenclature: Cabbage, *Brassica oleracea* L. var. *capitata*; buckwheat, *Fagopyrum esculentum* Moench; Tartary buckwheat, *Fagopyrum tataricum* (L.) Gaertn.

Key words: Conservation tillage, no tillage, roller-crimper, sickle-bar mower, soil compaction, soil nitrate–nitrogen.

The benefits cover crops provide to farms and the environment are widely recognized (Clark 2008; Teasdale et al. 2007). In Wisconsin, many organic vegetable growers plant buckwheat as a summer cover crop for diverse rotations (J Hendrickson, personal communication). Buckwheat is a broadleaved annual species that is valued as a summer cover crop for its quick growth, weed suppressive ability, and ease of management (Kumar et al. 2011). In a 2006 survey of 70 Wisconsin and Illinois vegetable growers, 78% reported using buckwheat cover crops, with over a third of respondents using them every year (J Hendrickson, unpublished data). Previous research has detailed the positive effects of buckwheat cover crops on soil tilth in Quebec (N'Dayegamiye and Tran 2001), weed suppression in New York (Kumar et al. 2011) and New England (Schonbeck 1991), phosphorus availability in Australia (Zhu et al. 2002), and promoting beneficial insect populations in New Zealand (Araj et al. 2009). Buckwheat has been shown in a number of studies in the United States and abroad to suppress problematic weed species, e.g., Canada thistle [*Cirsium arvense* (L.) Scop.] (Bicksler and Masiunas 2009), quackgrass [*Elymus repens* (L.) Gould.] (Golisz and Gawronski 2003), and Powell amaranth (*Amaranthus powelli* S. Wats.) (Kumar et al. 2009a). Additionally, previous research has suggested that buckwheat cover crops are associated with allelopathic activity (Iqbal et al. 2003; Kalinova 2004; Tominaga and Uezu 1995). Active phytochemicals include rutin, gallic acid, quercetin, and to a lesser extent other phenolics and flavonoids (Golisz et al. 2007).

Tartary buckwheat is a related species to buckwheat with many of the same traits valued in buckwheat as a cover crop. It is self-pollinating, relatively frost tolerant, and has a similar growth habit and phenology to buckwheat. Campbell (1997) indicated that Tartary buckwheat has higher

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* Graduate Student, Professor, and Professor, Department of Agronomy, University of Wisconsin–Madison, Madison, WI 53706. Current address of first author: Assistant Professor, Sustainable Agriculture Enterprise, Center for Sustainability and Global Change, Unity College, Unity, ME 04988. Corresponding author's E-mail: destolte@wisc.edu

vigor and potentially greater biomass production than buckwheat. Tartary buckwheat also contains high levels of potentially allelopathic phytochemicals in the vegetation (Fabjan et al. 2003) and seeds (Briggs et al. 2004).

In a web-based survey of Wisconsin vegetable farmers, we found most growers terminate buckwheat using tillage with a rotary tiller (Saunders Bulan 2014), although some growers allow the cover crop to frost-kill. Tillage used for cover crop termination prior to cash crop planting serves additional functions of field preparation, surface residue incorporation, and stimulating nutrient mineralization (Peigné et al. 2007). Conventional tillage (CT), defined as inversive cultivation leaving less than 30% of crop residues on the soil surface (Peigné et al. 2007), has been shown to reduce soil compaction and improve crop root growth and exploration (Vakali et al. 2011), and can increase yield relative to conservation-tillage systems (Deike et al. 2008). Bjorkman and Shail (2013) found conventional tillage following a vegetable crop improved establishment of buckwheat cover crops relative to conservation tillage.

Despite these benefits, frequent tillage can result in long-term soil structural degradation and erosion, leading to water, air, and soil quality problems (Holland 2004). Conservation tillage in contrast, improves soil agronomic and environmental health parameters over time (ACT 2008; Farooq et al. 2011; Hobbs et al. 2008; Holland 2004; Huggins and Reganold 2008; Montgomery 2007). In addition to the longer time scale before yield improvements, development of a conservation-tillage system for any given crop is a challenging endeavor that requires accounting for effects of temperature, timing, moisture, soils, cash crop, cover crop, weed and pest dynamics, economic feasibility, equipment, and grower training.

In agronomic crops, conservation-tillage has increased so as to be the norm in some areas for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] (Horowitz et al. 2010). There has also been increasing success with conservation-tillage vegetable production, due to increased grower expertise and availability of appropriately scaled specialized equipment (Morse 1999). However, challenges for conservation-tillage vegetable production remain: production of a dense, evenly distributed cover crop before transplanting; effective cover-crop termination resulting in adequate, uniformly distributed mulch; establishment of vigorous transplants with minimum surface soil/mulch disturbance; and effective year-round weed control (Morse 1999). Whereas the use of glyphosate-resistant crops has bolstered adoption of conservation tillage in agronomic crops (Dill et al. 2008), this technology remains unavailable to most vegetable growers.

In no-tillage (NT) systems, the cover-crop termination method is an important element. A recurring theme from recent research on NT organic farming is that efficacy must be improved when relying on killed cover-crop mulch for weed suppression (Carr et al. 2012). In a review of various methods of mechanical cover-crop termination, including mowing and roller-crimping, Creamer and Dabney (2002) described important considerations in choosing a mechanical termination method. Mowing is one of the most common methods for cover-crop termination, and different types of mowers have different levels of effectiveness with different cover-crop species. Creamer and Dabney (2002) cited studies in Louisiana, Ohio, and Mississippi in concluding that mowing is most effective for annual, erect-growing broadleaved crops, especially at later growth stages.

The roller-crimper, adapted from Latin American agriculture and popularized in the United States over the last decade, is a cylindrical implement that kills mature cover crops by crushing the stems (Walters 2005). The roller-crimper leaves the cover crop relatively intact, and in contrast to mowing, the residues form a uniform layer of protective mulch on the soil surface. Morse (1995) found mature buckwheat and foxtail millet [*Setaria italica* (L.) P. Beauv.] cover crops were effectively killed by rolling prior to transplanting sprouting broccoli (*Brassica oleracea* L. var. *italica* Plenck). Bernstein et al. (2011, 2014) found similar weed suppression between sickle-bar mowing and roller-crimping in transitional organic-soybean systems. However, some studies have shown weed persistence to be greater after rolling compared to mowing (Creamer and Dabney 2002; Silva 2013).

Managing NT summer cover crops for fall vegetable production poses particular challenges in the northcentral United States because a short growing season constrains growth of cover-crop biomass required for weed suppression. Yet conservation-tillage management has achieved some success in several summer cover-crop fall-vegetable systems. Compared with tilled bare ground, NT vegetable production after a summer cover crop has shown equal or greater yields for lettuce (*Lactuca sativa* L.) (Wang et al. 2008), broccoli (Abdul-Baki et al. 1997; Morse 1995), and onions (*Allium cepa* L.) (Vollmer et al. 2010).

Cabbage is an important vegetable crop in Wisconsin grown on over 1,200 ha and with a value of over $11.2 million in 2012 (USDA 2013). Several studies have investigated conservation-tillage production of cabbage, with mixed success. In a cereal rye (*Secale cereale* L.) cover-crop, strip-tilled cabbage yields were 56% greater compared to conventional tillage under very dry conditions in Virginia (Wilhoit et al. 1990). However, Hoyt and Walgenbach (1995) reported reduced yields in strip-tilled cabbage in North Carolina. Reduced cabbage yields have also been found in conservation-tillage systems using cover crops of hairy vetch (*Vicia villosa* Roth), perennial ryegrass (*Lolium perenne* L.), and cereal rye compared to conventional tillage (Masiunas et al. 1997; Roberts et al. 1999).

If yield reduction can be overcome, cabbage producers can reap many of the benefits often associated with conservation tillage. Masiunas et al. (1997) found cover-crop mulches in cabbage production systems can increase soil conservation, suppress weeds, and provide habitat for beneficial organisms, and a number of reports have found fewer pests in conservation-tillage cabbage production (Borowy 2004; Hoyt and Walgenbach 1995; Roberts et al. 1999).

Our research objectives were to determine the effectiveness of Tartary buckwheat relative to buckwheat for weed suppression during the cover-cropping phase and after cover-crop termination during cabbage production, and to quantify weed suppression, soil moisture and compaction, soil nitrogen availability, and cabbage yield in no-tillage (roller-crimped or sickle-bar mowed) and conventional-tillage (rototilled) systems.

Materials and Methods

Site Description and Field Procedures. Experiments were conducted on certified organic land at the University of Wisconsin West Madison Agricultural Research Station (WM, 43.065°N, 89.535°W) in 2010 and 2011, and conventionally managed land at the University of Wisconsin Arlington Agricultural Research Station (AR, 43.314°N, 89.336°W) in 2011. The soil type at WM was a Kegonsa silt loam with 2.9% organic matter and pH 7.1. The soil type at AR was a Plano silt loam with 4.0% organic matter and pH 7.3. Plots were laid out in an expanded factorial design with four replications of treatments per site-year. In 2010, five treatments were established: no-tillage (NT) mowed buckwheat, conventional-tillage (CT) buckwheat, NT mowed Tartary buckwheat, CT Tartary buckwheat, and a fallow control. In CT plots, cover crops were terminated using a rototiller (1.5 m wide, Land Pride RTA 2570; Land Pride, Salina, KS); fallow plots were also managed using CT prior to cabbage transplanting. In 2010, cover crops were mowed using a sickle-bar mower (0.81 m wide, JARI Monarch; JARI, St. Peter, MN). In 2011, NT treatments were expanded to include two cover-crop termination methods: a roller-crimper (4.6 m wide; I and J Manufacturing, Gap, PA) and a sickle-bar mower (2.1 m wide; John Deere 350, Moline, IL). Plots at WM in 2010 measured 2.4 m by 15.2 m. The inclusion of the roller-crimper in 2011 necessitated widening the plots to 4.3 m by 12.2 m at WM and 6.1 m by 9.1 m at AR.

Seeding rate was 90 kg ha^{-1} for buckwheat and 73 kg ha^{-1} for Tartary buckwheat, which due to seed size differences resulted in approximately equal population densities (Table 1). Seeding rates were consistent with recommendations in the literature (Bjorkman and Shail 2010). Because of low populations in 2010, Tartary buckwheat seeding rate was increased to 90 kg ha^{-1} in 2011.

Daily temperature and precipitation data were retrieved from weather stations located within 1 km of research sites: Charmany Farm (WM, station USC00471416) and Arlington University Farm (AR, station USC00470308). Weather data were retrieved from the Global Historical Climatology Network—Daily Database maintained by the National Climatic Data Center (Menne et al. 2012).

Data Collection. One permanent quadrat (1 m by 1 m) was established in each treatment plot for repeat counts of cover-crop and weed emergence. Counts were made twice weekly in the first 3 wk following planting, and then once weekly until the end of the 6-wk cover cropping period (Table 1). Weeds were identified to the genus level, and each counted plant was marked with a small wooden stake to prevent double counting.

In addition to permanent quadrats, weekly destructive samples (0.25 m by 0.25 m) were randomly harvested from each treatment beginning 2 wk after planting (Table 1). Aboveground biomass was cut and partitioned into cover crop and weed components. Weeds were identified to genus level, counted, and weighed fresh. Cover-crop plants were also counted and weighed fresh. After cover-crop termination in mid-July, weed biomass

Table 1. Timing of field operations and data collection for experiments conducted at the University of Wisconsin West Madison Agricultural Research Station (WM) in 2010 and 2011 and the University of Wisconsin Arlington Agricultural Research Station (AR) in 2011.[a]

Activity	Site and year		
	WM 2010	WM 2011	AR 2011
Cover-crop planting date	June 3	May 31	June 1
Buckwheat seeding rate (viable seeds ha^{-1})	2.49×10^6	2.49×10^6	2.49×10^6
Tartary buckwheat crop seeding rate (viable seeds ha^{-1})	2.49×10^6	3.66×10^6	3.66×10^6
Buckwheat stand density 40 DAP (plants m^{-2})	146	100	102
Tartary buckwheat stand density 40 DAP (plants m^{-2})	100	93.7	84.0
Emergence counts	June 7, 10, 14, 18, 21, 24, 30; July 7	June 6, 9, 13, 17, 20, 22, 29; July 5	June 7, 9, 13, 16, 21, 23, 30; July 6
Pretermination cover-crop and weed biomass sampling	June 15, 22, 28; July 8, 13	June 17, 22, 29; July 5, 13	June 16, 23, 30; July 6, 15
Cover-crop termination	July 14	July 13	July 15
Posttermination weed biomass sampling	July 29; Aug 11	August 4, 26; Sept 20	Aug 3, 25; Sept 18
Cabbage planting	July 14	July 14	July 18
Soil nitrate–nitrogen (NO_3–N) sampling	July 14	July 14	July 15
Soil penetrometer measurements	nc	July 29	July 29
Cabbage harvest	nc	Oct 11	Oct 12

[a] Abbreviations: DAP, d after planting; nc, data not collected.

samples were collected from plots at 3-wk intervals. After fresh weight measurements were taken, all samples were dried for 1 wk and weighed.

Soil Measurements. Immediately after cover-crop termination, four soil cores per plot were extracted from a 15 cm depth using a 1.9-cm-diam probe, composited, and delivered to the University of Wisconsin–Madison Soil Testing Laboratories (Verona, WI). Samples were processed and rapid-dried at 55 C for analysis of nitrate–nitrogen (NO_3–N) concentration (Table 1). Soil compaction can inhibit growth and depress yield for both direct-seeded and transplanted cabbages (Wolfe et al. 1995). Two wk after cabbage planting in 2011, following a soaking rain, cone penetrometer readings were taken in five randomized locations in each plot at each site (Van Huyssteen 1983). Penetrometer resistance is a commonly used measure of compaction, with an accepted threshold for growth-limiting compaction at 2,000 kPa (Utset and Cid 2001) or about 300 psi (Van Huyssteen 1983). For each measurement, penetration resistance in the soil profile was recorded at six evenly spaced depths between 7.5 and 45.5 cm. Because spatial variability in penetrometer resistance can be due to different soil moisture contents (Anderson et al. 1980), we concurrently measured soil moisture at three locations within each plot to a depth of 20 cm using a soil moisture meter (FieldScout 300 TDR; Spectrum Technologies Inc., Aurora IL).

Cabbage Yield. Copenhagen, a 65 to 75 d cabbage variety, was hand-transplanted into plots within 1 d of cover-crop termination. All cabbages were planted concurrently to limit the confounding effects between CT and NT treatments. To account for effects of weed competition on cabbage yield, a section of each plot containing 16 cabbages was hand-weeded twice during the course of the growing season. In 2010, no cabbages were harvested due to complete crop loss from weed competition in NT treatments. In 2011, cabbages were harvested by hand on October 11 and 12 and WM and AR, respectively. Harvested cabbage weight and head diameter were measured.

Data Analysis. Analyses were performed using R statistical software (R Core Team 2013). Treatment effects and interactions were tested using ANOVA. Data were pooled for analysis if there were no site-year by treatment interactions. In order to better understand weed suppressive potential of buckwheat and Tartary buckwheat, cover-crop emergence timing and shoot biomass accumulation were modeled based on thermal time (Edwardson 1995; Gorski 1986). Accumulated thermal time, measured in growing degree days (GDD), was calculated according to the mean-minus-base method (Equation 1):

$$GDD = (T_{max} + T_{min})/2 - T_{base} \quad [1]$$

where T_{max} is the maximum daily temperature, T_{min} is the minimum daily temperature, and T_{base} is the base temperature for buckwheat, set at 5 C (Edwardson 1995; Gorski 1986). The STM2 model in WeedCast (Spokas and Forcella 2009) was used to convert air temperature data to soil temperatures for calculation of GDD.

Cover-crop emergence data were normalized by plot to allow model fitting. The *grofit* package in R was used to fit a biological growth curve to emergence data (Kahm et al. 2010). The *grofit* package tested several parametric growth models: logistic, Gompertz, modified Gompertz, and Richards. Model parameters defined comparable S-shaped growth curves, with upper asymptote (A), slope (mu), and lag-time (lambda) terms. The Akaike Information Criterion (AIC) was used to determine the best-fitting model, and model parameters were compared among treatments using 95% confidence intervals. Maximum cover-crop emergence was analyzed for each site-year using two-way ANOVA.

A logistic growth function best described cover-crop shoot biomass accumulation. The function was fit to data pooled over site-years using *nls* and self-start logistic function *SSlogis* in the R base package as described by Pinheiro and Bates (2000). *SSlogis* fits a sigmoid function of the form (Equation 2):

$$Y = Asym/\{1 + \exp[(xmid - \text{time})/scal]\} \quad [2]$$

where *Asym* is the upper asymptote, *xmid* is the location of the inflection point, and *scal* is a numeric scale parameter relating the approximate distance on the x-axis from 50 to 75% of *Asym*. Model parameters for the functions were compared using 95% confidence intervals generated by Beale's method implemented in the *nlstools* package in R (Baty and Delignette-Muller 2013).

A mixed linear model in the *nlme* package in R (Pinheiro et al. 2014) was fit to weed shoot biomass accumulation during the cover-cropping phase. Biomass data were log-transformed to improve homoscedasticity of residuals. Parameter significance of mixed models was tested using 95% confidence intervals implemented in *nlme*. R^2 values for mixed linear models were calculated using the method described by Nakagawa and Schielzeth (2013) and code for the *rsquared.glme* function (Lefcheck 2013).

A linear model was fit to weed biomass post-cover-crop termination, with site-year as a random effect. ANOVA was used to compare means of cabbage yield and NO_3–N concentrations among treatments. Cabbage yields under weed-free and weedy conditions were compared within treatment using a *t* test. Penetrometer readings were compared among treatments at measured depths using standard error of the mean. A priori "dummy variable" contrasts were used to determine the main effect of cover-crop treatment on cabbage yield, and compare mean response of cabbage yield between NT and CT treatments and the two NT cover-crop termination methods using the treatment contrast method outlined in Crawley (2007). Means separation was performed using Tukey's HSD implemented in the general linear hypothesis test *ghlt* function of the *multcomp* package in R (Hothorn et al. 2008). Data were pooled when there was no significant treatment by site-year interaction.

Results and Discussion

Weather Patterns. In 2010, rainfall during the cover-crop–growing period was about twice the 30-yr average (Figure 1). Rainfall in 2011 was slightly less than the 30-yr average. Accumulated heat units were similar to the long-term average across site-years, but temperatures at the WM site tended to be warmer than at the AR site in both years.

Cover-crop Emergence and Growth. Buckwheat emerged earlier than Tartary buckwheat, demonstrating greater weed competitiveness (Figure 2, Table 2). The best-fit model for Tartary buckwheat data was a logistic model and buckwheat was best described by a Gompertz model. Lag time was shorter for buckwheat emergence than for Tartary; other growth parameters did not differ.

We did not find a consistent difference in maximum seedling emergence between the two cover-crop species; however, site-years interacted significantly with cover-crop treatment for maximum emergence (data not shown). At WM in 2010, maximum emergence of buckwheat was greater than Tartary buckwheat, with 105 and 70 seedlings m^{-2} for buckwheat and Tartary buckwheat, respectively. In 2011, maximum emergence did not differ between cover crops at either site with a mean emergence of 180 seedlings m^{-2} at AR and 114 seedlings m^{-2} at WM. Differences in soil type, seedbed quality, and seeder precision might have led to differences between the sites.

Cover-crop Biomass. Both buckwheat species displayed logistic biomass accumulation patterns. Buckwheat accumulated 64% more maximum shoot dry biomass than Tartary buckwheat (Figure 3, Table 3). The time in heat units to 50% and 75%

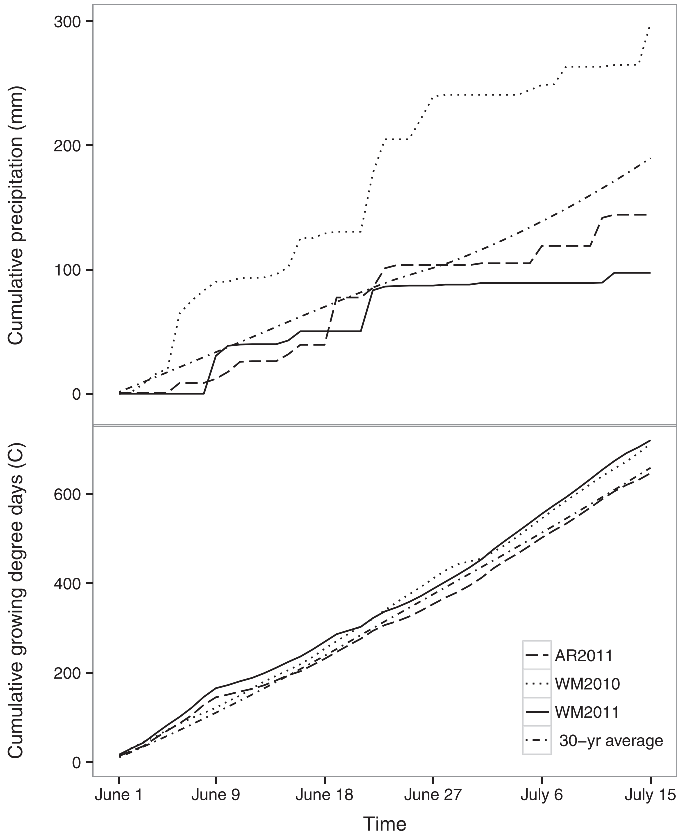

Figure 1. Cumulative precipitation and growing degree days (GDD) for experiments conducted at the University of Wisconsin West Madison Agricultural Research Station (WM) in 2010 and 2011 and the University of Wisconsin Arlington Agricultural Research Station (AR) in 2011. Thirty-yr (1980 to 2009) averages for pooled WM and AR sites are shown. Thermal time was calculated using a base temperature of 5 C for buckwheat species.

of maximum biomass accumulation did not differ between cover-crop species.

Weed Communities and Biomass Accumulation. The weed community at the AR site was dominated by pigweeds (*Amaranthus* spp.), followed by foxtails (*Setaria* spp.) and velvetleaf (*Abutilon theophrasti* Medik.) (Table 4). At the WM site in 2010, pigweeds were the most abundant weed type, followed by common lambsquarters (*Chenopodium album* L.) and foxtails. In 2011, foxtails were most abundant, followed by pigweed species and ladysthumb (*Polygonum persicaria* L.). Bjorkman and Shail (2013) found pigweed species are most likely to escape in a buckwheat stand. This is consistent with our results, especially in the wetter 2010 season.

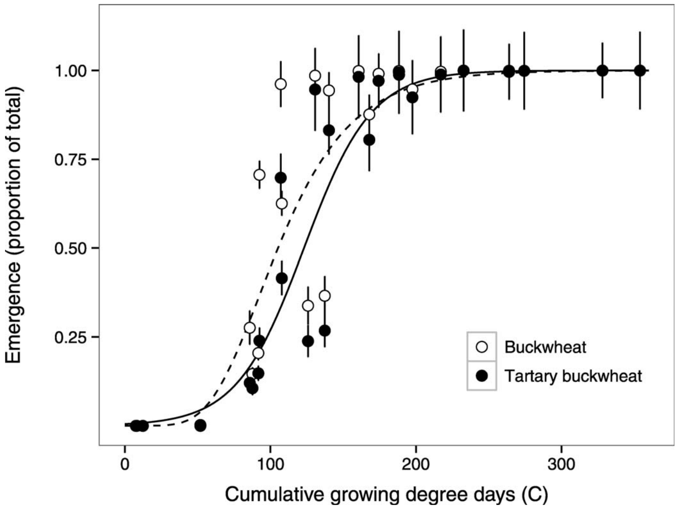

Figure 2. Cumulative emergence of buckwheat (dashed line) and Tartary buckwheat (solid line) as a function of thermal time across three site-years in 2010 and 2011. Best-fit models were the Gompertz function for buckweat and a logistic function for Tartary buckwheat. Equation parameter estimates are shown in Table 2. Initial time for calculating cumulative growing degree days (base temperature 5 C) was June 1. Vertical bars depict standard error of the mean.

The rate of weed shoot biomass accumulation was correlated with increasing GDD, but did not differ among treatments (data not shown). Measured weed shoot biomass prior to termination was less for the buckwheat treatment than the Tartary buckwheat treatment in two of three site-years, and was less than that for the fallow treatment across all site-years (Table 5). Weed suppression in the

Table 2. Emergence model parameter estimates for buckwheat and Tartary buckwheat across three site-years in 2010 and 2011. Seedling emergence was regressed against thermal time expressed in growing degree days (GDD, base temperature 5C) from June 1. Responses are described by $Y = 1.02 * \exp[-\exp((0.0106/1.01) * (58.0 - GDD) + 1)]$ and $Y = 1.01/(1 + \exp((4 * 0.0108) * (76.8 - GDD) + 2))$ for buckwheat and Tartary buckwheat, respectively.

	Emergence model parameter		
Cover crop	Maximum rate	Maximum	Lag time
	Proportion of total emergence GDD^{-1}	Proportion of total	GDD
Buckwheat	0.0106 a[a]	1.02 a	58.0 a
Tartary buckwheat	0.0108 a	1.01 a	76.8 b

[a] Within columns, means followed by the same letter do not differ using 95% confidence intervals generated by a nonparametric bootstrap method in the *grofit* package in R.

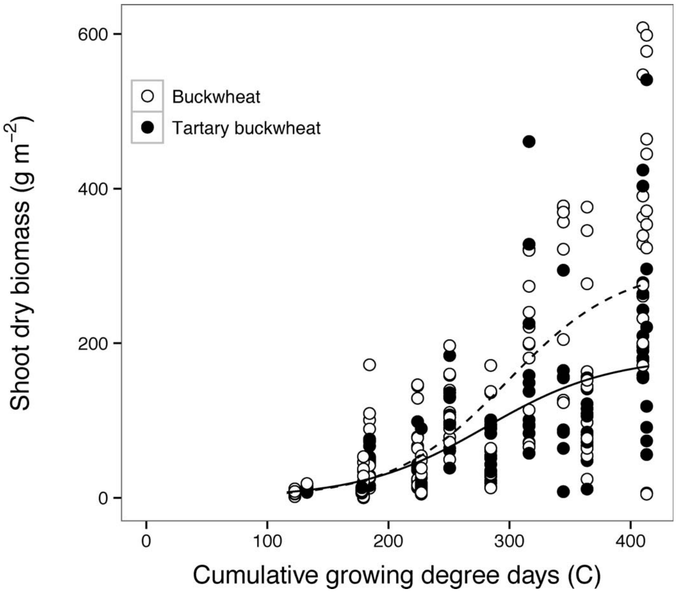

Figure 3. Logistic shoot dry biomass accumulation of buckwheat (dashed line) and Tartary buckwheat (solid line) as a function of thermal time expressed in growing degree days (base temperature 5C) from June 1 across three site-years in 2010 and 2011. Equations are shown in Table 3. Symbols represent sampled plot values.

Tartary buckwheat treatment at WM in 2011 compared to 2010 was likely due to the increased seeding rate and improved stand establishment.

Soil Compaction, NO_3–N Concentration, and Soil Moisture. The site and cover-crop treatment interaction was significant for soil compaction, NO_3–N concentrations, and soil moisture (data not shown). Mixed models for NO_3–N concentrations were fit for each site, with year as a random variable. The best-fit model included cover-crop treatment and termination method as fixed effects. Soil NO_3–N concentration did not differ between sickle-bar mower and roller-crimper termination treatments (data not shown) so data were pooled and analyzed as a no-tillage (NT) treatment. NO_3–N concentrations in mid-July (taken within 1 d of cover-crop termination) tended to be greater in conventional tillage (CT) than in NT treatments (Table 6), indicating N mineralization from incorporated biomass. At the AR site, soil NO_3–N concentration was greater in the fallow treatment than in cover-cropped treatments, but at the WM site, NO_3–N concentrations did not differ between fallow and CT cover-cropped treatments. NO_3–N concentrations did not differ between the two buckwheat cover crops in either tillage treatment.

Our finding that tillage affected available nitrogen more than cover-crop species is consistent with recent research. In a study using diverse cover-crop mixtures in Nebraska, Wortman et al. (2012) found soil NO_3–N was affected by cover-crop termination method, with greater NO_3–N using a sweep plow undercutter compared to disk incorporation. Some of the greatest soil NO_3–N concentrations were in weedy undercut treatments, but soil NO_3–N was inconsistent among other cover-crop and termination treatments.

Penetrometer readings in late July differed between sites and tillage treatments, with growth-limiting soil compaction (greater than 2,000 kPa penetrometer resistance) in NT occurring at shallower soil depths at the AR site compared to the WM site (Figure 4). At the AR site, the 2,000 kPa threshold in NT was surpassed at 15 cm, whereas the CT treatment showed less compaction for the entire measured depth of the soil profile, and did not exceed 2,000 kPa. Below 15 cm, soil was less compacted in the NT sickle-bar mowed treatment the roller-crimped treatment. Greater soil compaction at these depths in the roller-crimper treatment might have been due to greater soil moisture, but we did not take measurements below 20 cm. At the WM site, penetrometer resistance at shallow ($<$ 23 cm) soil depths was lower overall than at the AR site. Both NT treatments showed a similar pattern of resistance, exhibiting greater penetrometer resistance than the CT treatment at each measurement depth to 30 cm. Soil moisture

Table 3. Logistic model parameter estimates for buckwheat and Tartary buckwheat cover-crop shoot dry biomass accumulation as a function of thermal time expressed in growing degree days (GDD, base temperature 5C) from June 1 across three site-years in 2010 and 2011. Responses are described by $Y = 301.4/(1 + \exp((298.2 - GDD)/47.16))$ and $Y = 182.7 (1 + \exp((280.2 - GDD)/51.48))$ for buckwheat and Tartary buckwheat, respectively.

Cover crop	Maximum mass	Time to 50% maximum mass	Time from 50 to 75% maximum mass
	g m^{-2} dry	GDD	GDD
Buckwheat	301 a[a]	298 a	47 a
Tartary buckwheat	183 b	280 a	51 a

[a] Within columns, means followed by the same letter do not differ at 0.05 level using Beale's method in the *nlstools* package in R.

Table 4. Proportional shoot dry biomass of 10 major weed species or genera prior to buckwheat cover-crop termination. Experiments were conducted at the University of Wisconsin West Madison Agricultural Research Station (WM) in 2010 and 2011 and the University of Wisconsin Arlington Agricultural Research Station (AR) in 2011. Data were pooled over buckwheat cover-crop treatments.

			Proportion of total weed shoot biomass		
Common name	Latin name	Bayer code	WM2010	WM2011	AR2011
Pigweed species	*Amaranthus hybridus* L. *Amaranthus retroflexus* L.	AMACH AMARE	0.3437	0.2138	0.5618
Foxtail species	*Setaria faberi* Herrm. *Setaria pumila* (Poir.) Roemer & J. A. Schultes	SETFA SETLU	0.2309	0.5965	0.1257
Common lambsquarters	*Chenopodium album* L.	CHEAL	0.3125	0.0530	0.0191
Ladysthumb	*Polygonum persicaria* L.	POLPE	0.0600	0.0755	0.0095
Yellow nutsedge	*Cyperus esculentus* L.	CYPES	0.0076	0.0005	0.0000
American black nightshade	*Solanum americanum* P. Mill.	SOLAM	0.0016	0.0190	0.0008
Potato, volunteer	*Solanum tuberosum* L.	SOLTU	0.0252	0.0000	0.0000
Cereal rye, volunteer	*Secale cereale* L.	SECCE	0.0147	0.0258	0.0012
Shepherd's purse	*Capsella bursa-pastoris* (L.) Medik	CAPBP	0.0023	0.0022	0.1010
Velvetleaf	*Abutilon theophrasti* Medik.	ABUTH	0.0008	0.0102	0.1732

availability in the top 20 cm of the soil profile in late July was more variable at WM than at AR, but was not related to cover-crop management, cover-crop species, penetrometer resistance, or cabbage yield at either site (data not shown). Cabbage yield can be greatly reduced by soil compaction. Wolfe et al. (1995) found a 73 and 29% reduction in harvestable yield of direct-seeded and transplanted cabbages, respectively, in treatments with 2,000 kPa penetrometer resistance at soil depths between 7 and 30 cm.

Posttermination Weed Growth. The termination by cover-crop interaction was not significant, so data were pooled over cover-crop species for analysis (data not shown). After cover-crop termination, weed shoot biomass in all management treatments increased with thermal time, but the rate of increase did not differ among treatments (Figure 5). However, weed shoot biomass was greater in NT than in CT treatments, and overall weed shoot biomass was greater in the roller-crimped treatment than the sickle-bar mowed treatment. We attributed greater weed biomass in NT to the survival of weeds in the cover-crop understory and lack of sufficient surface mulch to suppress weed growth. After NT cover-crop termination, weeds that were already established beneath the cover-crop canopy thrived. In the CT treatments, established weeds were killed by tillage after which there was relatively little additional weed emergence and growth.

Cabbage Yield. Cabbage yield was not affected by cover-crop species in CT or NT treatments (Table 7). Moreover, yields did not differ between NT sickle-bar mowed or roller-crimped treatments. However, cabbage yield was greatly affected by tillage treatment. Cabbage yields in weed-free CT treatments were similar to the Wisconsin statewide average of 35.9 Mg ha^{-1} in 2011 (USDA 2014), but yields were much less in NT treatments. Average cabbage yield in CT treatments was 5- and 12-fold greater than in NT treatments under weed-free and weedy conditions, respectively. At

Table 5. Mean weed shoot dry biomass in fallow, buckwheat, and Tartary buckwheat cover-crop treatments prior to cover-crop termination at the University of Wisconsin West Madison Agricultural Research Station (WM) in 2010 and 2011 and the University of Wisconsin Arlington Agricultural Research Station (AR) in 2011. Biomass was measured at 403 growing degree days (GDD, base temperature 5 C, from June 1) at WM in 2010, 354 GDD at WM in 2011, and 400 GDD at AR.

Treatment	Weed shoot dry biomass		
		g m^{-2}	
	WM2010	WM2011	AR2011
Fallow	232 a[a]	113 a	61 a
Buckwheat	63 b	23 b	6 b
Tartary buckwheat	204 a	27 b	33 a

[a] Within a column, values followed by the same letter do not differ based on ± 1 standard error of the mean.

Table 6. Soil nitrate–nitrogen concentrations in conventional-tillage (CT) and no-tillage (NT) buckwheat and Tartary buckwheat cover-crop treatments posttermination (pooled over termination treatments) at the University of Wisconsin West Madison Agricultural Research Station (WM) in 2010 and 2011 and the University of Wisconsin Arlington Agricultural Research Station (AR) in 2011.

		Soil nitrate–nitrogen		
Tillage	Cover-crop treatment	WM 2010	WM2011	AR2011
		ppm		
CT	Fallow	11.22 a[a]	17.41 a	27.10 a
CT	Buckwheat	8.83 abc	15.03 abc	18.30 bc
CT	Tartary buckwheat	9.34 ab	15.54 ab	19.45 b
NT	Buckwheat	4.84 c	11.04 c	13.22 cd
NT	Tartary buckwheat	5.04 bc	11.24 bc	11.80 d

[a] Within a column, numbers followed by the same letter do not differ at the 0.05 level determined by Tukey's HSD.

a cabbage crop value of \$328 Mg^{-1} (USDA 2014), the average loss in NT compared to CT would be \$10,000 and \$8,000 ha^{-1} in weed-free and weedy conditions, respectively.

Our results indicate that Tartary buckwheat was a less effective cover crop than buckwheat, performing the same or worse than buckwheat across all horticulturally important parameters. Tartary buckwheat emerged later and produced less total biomass than buckwheat, and allowed for faster weed growth and weed biomass accumulation. Cabbage yields did not differ between CT cover-cropped treatments and the fallow check treatment. Wisconsin growers expect yields of about 2 kg head^{-1} for late cabbage (Delahaut and Newenhouse 1997). In our study, cabbages from the CT treatments averaged 1.7 kg head^{-1}, and cabbages in the NT treatments averaged only 0.3 kg head^{-1}. A high incidence of cabbage loopers (*Trichoplusia ni* Hubner) at both sites likely reduced yield compared to that of a conventional cabbage production system that would typically include pesticide use.

Regarding nutrient dynamics, buckwheat biomass incorporated into the soil in CT treatments

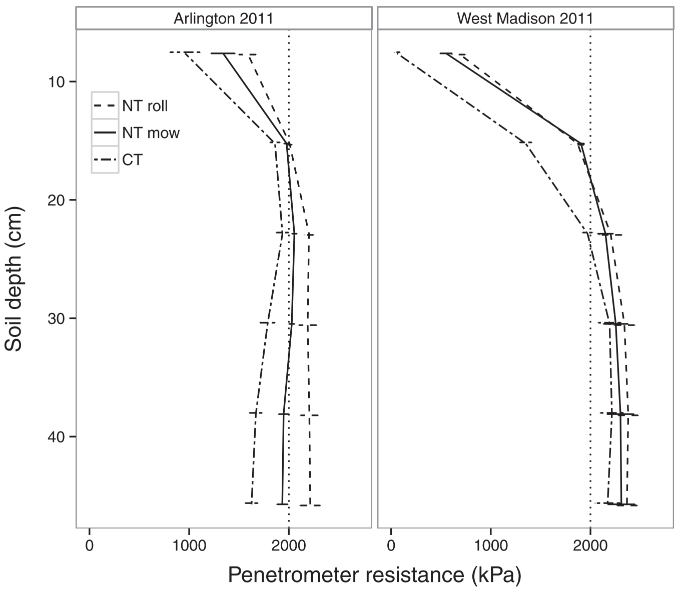

Figure 4. Soil penetrometer resistance in no-tillage (NT) roller-crimped (roll) and sickle-bar mowed (mow) buckwheat cover-crop treatments posttermination (pooled over buckwheat species) and a conventional-tillage (CT) treatment at the University of Wisconsin West Madison Agricultural Research Station (WM) and the University of Wisconsin Arlington Agricultural Research Station (AR) in 2011. Horizontal bars represent standard error of the mean. Dotted vertical lines represent the root growth limiting resistance threshold at 2,000 kPa.

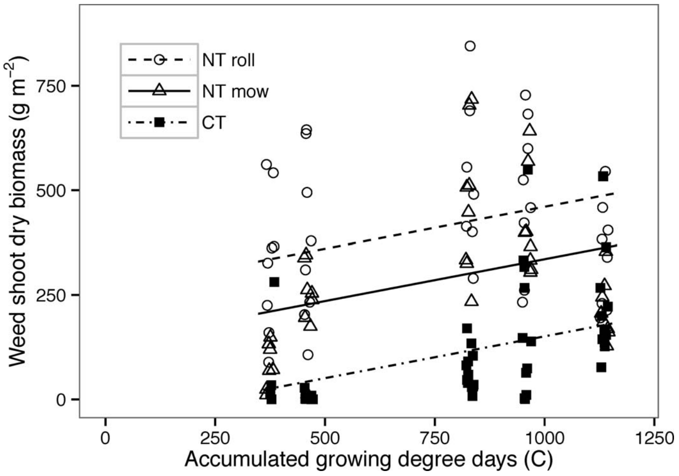

Figure 5. Weed shoot dry biomass in no-tillage (NT), roller-crimped (roll), and sickle-bar mowed (mow) buckwheat cover-crop treatments posttermination (pooled over buckwheat species) and a conventional-tillage (CT) treatment at the University of Wisconsin West Madison Agricultural Research Station (WM) and the University of Wisconsin Arlington Agricultural Research Station (AR) in 2011. Growing degree days (GDD, base temperature 5 C) were calculated from the time of cover-crop termination at each site, July 13 at WM and July 15 at AR. Data were pooled over sites and buckwheat cover crops. Model takes the form $Y = GDD + mgmt$. The linear model specified different intercepts for each treatment but equal slope values. Intercept estimates (standard error) for NT roll = 260.1 (43.8), NT mow = 135.2 (35.0), CT = −49.29 (33.1). Slope values were positive and did not differ among treatments, slope (standard error) = 0.2002 (0.048) g m^{-2} GDD^{-1}.

Table 7. Cabbage yield in weed-free and weedy conditions as affected by cover-crop treatment and termination method: conventional tillage (CT), no-tillage (NT) roller-crimped (roll), or sickle-bar mowed (mow). Experiments were conducted at the University of Wisconsin West Madison Agricultural Research Station and Arlington Agricultural Research Station in 2011. Data were pooled over sites.

Cover-crop treatment	Termination method	Yield Weed-free	Yield Weedy
		tons ha^{-1}	
1 Fallow	CT	40.0 a[a]	24.2 a*
2 Buckwheat	CT	31.5 ab	25.7 a
3 Tartary buckwheat	CT	42.1 a	29.8 a
4 Buckwheat	NT roll	6.5 c	0.7 b*
5 Tartary buckwheat	NT roll	2.1 c	0.0 b*
6 Buckwheat	NT mow	7.8 c	0.0 b*
7 Tartary buckwheat	NT mow	13.4 bc	8.1 b
Contrast		P value	
CT (1,2,3) vs. NT (4,5,6,7)		< 0.0001	< 0.0001
Fallow (1) vs. CT cover crop (2,3)		NS[b]	NS
NT roll (4,5) vs. NT mow (6,7)		NS	NS

[a] Within columns, means followed by the same letter do not differ at the 0.05 level using Tukey's HSD. Within rows, an asterisk (*) indicates that means differed between weed-free and weedy conditions at the 0.05 level using a *t* test.

[b] Abbreviation: NS, not significant.

might have led to greater N immobilization relative to the fallow treatment, as indicated by the differences in NO_3–N concentrations between these treatments at the AR site. Although this discrepancy did not appear to affect cabbage yields in our study, other studies have found that the incorporation of organic residues might result in delayed N availability to a subsequent crop (Clark et al. 1999; Garton 1994). Synchronization between crop N demand and release of N from abundant buckwheat residues could potentially increase crop yield and reduce N leaching relative to weedy tilled land.

Terminating buckwheat cover crops with NT methods was ineffective, especially in the case of the roller-crimper. The cover crops regrew after both mowing and roller crimping, and competed with the cabbage crop. Both cover crops have succulent, flexible stems that were incompletely crushed under the roller crimper, after which plants recovered within a few days. Variability in plant maturity within the stand also contributed to incomplete cover-crop termination. Furthermore, weeds that survived beneath the standing cover crop grew quickly after the canopy was destroyed. We found that NT methods for cover-crop termination led to increased stand weediness and soil compaction relative to CT, and resulted in dramatic cabbage yield loss. Our results are consistent with the findings of Mischler et al. (2010) who found reduced corn yields after incomplete control of a hairy vetch cover crop.

Weed suppression by organic mulch is a complex phenomenon with multiple proposed and possibly interacting mechanisms, including physical interference, effects on nutrient dynamics, and allelopathy (Altieri et al. 2011; Creamer and Baldwin 2000). Perhaps the most important attribute of effective mulch is high biomass production. Teasdale and Mohler (2000) estimated that 75% weed suppression is possible only at biomass production above 8 Mg ha^{-1}. In contrast, buckwheat in our study produced an average of 2.8 Mg ha^{-1} for buckwheat and 1.9 Mg ha^{-1} for Tartary buckwheat. Our results are consistent with other studies (Creamer and Baldwin 2000; Kumar et al. 2009b) that found the biomass production of buckwheat is less than that of grass cover crops and much less than the 8 Mg ha^{-1} threshold.

Another potentially important factor affecting weed suppression is the relatively low C : N ratio of buckwheat biomass and associated rapid decomposition rate compared to grass species typically used in NT systems. Kumar et al. (2009b) calculated a C : N ratio of 8.5 for buckwheat, compared to a ratio of 24.8 for oat (*Avena sativa* L.), whereas Creamer and Baldwin (2000) found a C : N ratio of 21 for buckwheat compared to a ratio of 42 or greater for five grass cover-crop species. Buckwheat's rapid decomposition is valued by farmers because it improves ease of cover-crop management, but it likely reduces the long-term effectiveness of buckwheat mulches compared to grass mulches.

It is possible that NT summer buckwheat could be one component of a diversified weed management plan for cabbage production that includes the addition of mulch. In a study on organic collards production, Mulvaney et al. (2011) found a summer cover crop of forage soybean alone was ineffective for weed suppression, likely due to its rapid decomposition preventing a lasting mulch effect; yet mulch subtreatments of straw and leguminous perennial prunings suppressed weed populations. Multiple weed management tactics in addition to cover cropping are usually required, regardless of cash crop (Williams et al. 1998). A recent study evaluated 16 leguminous cover crops for use in no-tillage organic corn production and determined that none of these crops had the optimum combination of attributes (Parr et al. 2011).

The development of conservation-tillage systems for vegetable production is highly context-specific, and what has worked in one area is not necessarily effective in another (Roberts et al. 1999). Recent research found use of a conservation-tillage undercutter to have potential for effective cover-crop and weed management in organic cropping systems on silty clay loam soils (Wortman et al. 2012). In their research, a weed mixture-undercutter treatment was the most profitable in an organic common sunflower (*Helianthus annuus* L.)–soybean–corn rotation due to reduced input costs, suggesting that in certain contexts even weeds, if managed effectively, could play a productive role in NT systems. Although our research was not conducted entirely on certified organic land, the management methods tested are compatible with certified organic agriculture. As is typical with organic systems, the impact of particular management practices might only be apparent after multiple cycles, and not immediate as tends to be the case in conventional systems (Barberi 2002).

Buckwheat is planted by many Wisconsin farmers for its multiple benefits of weed suppression, beneficial insect habitat, soil improvement, ease of management, and erosion protection. For these qualities it is likely to remain a valued summer cover-cropping tool. However, our results indicate little reason for farmers to choose Tartary buckwheat over buckwheat in the situations we tested. Tartary buckwheat performed poorly in our study relative to buckwheat, due to its lag in emergence and subsequent reduced weed competitiveness. It is possible that in cooler seasons, the cold tolerance of Tartary buckwheat will provide some advantage over buckwheat, and the results of a late–summer-planted overwintering experiment suggest this might be the case (Saunders Bulan 2014). It is also possible that in southern Wisconsin, neither buckwheat species is a good candidate for no-tillage mulch systems compared with more vigorous grasses or mixtures. If either buckwheat species is to be used effectively in NT vegetable production, the major issues of weed suppression and creating a soil environment conducive for transplant crop establishment should be addressed.

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