

A Systems Comparison of Contrasting Organic Weed Management Strategies

Bryan Brown and Eric R. Gallandt*

Weed management strategies differ in their ability to control weeds, and often have unique agroecological implications. To provide growers with an improved sense of trade-offs between weed control and ecological effects, we implemented several prominent organic weed management strategies in yellow onion in 2014 and 2015. Strategies included cultivation of weed seedlings during the early, weed-sensitive “critical period” of the crop; frequent cultivation events to ensure “zero seed rain”; and weed suppression with polyethylene or natural mulches. As expected, end-of-season weed biomass and weed seed production were greatest in the critical period system and nearly zero for the zero seed rain system. Weeds were also well controlled in natural mulch systems. Average onion yield per treatment was 50.7 Mg ha⁻¹. In 2014, the critical period system and the polyethylene mulch systems demonstrated yield loss, likely due to weed competition and excessive soil temperature, respectively. Onion soluble solids content was also diminished in these systems in 2014, but bulb firmness was greatest in unmulched systems. Carabid beetles, earthworms, soil compaction, soil nitrate, and microbial biomass were affected by weed management strategy, with natural-mulched systems generally performing most favorably. However, these effects were not substantial enough to affect yield of a subsequent sweet corn crop grown in weed-free conditions. In contrast, sweet corn managed with only early-season cultivations demonstrated yield loss ($P = 0.004$) in plots where the critical period treatment was implemented the prior year, indicating that weed competition resulting from abundant weed seed production in that system was the most influential legacy effect of the weed management strategies.

Nomenclature: Onion, *Allium cepa* L.; corn, *Zea mays* L.

Key words: Critical period, mulch, organic management, systems comparison, weed management, zero seed rain.

Many farmers focus on early-season control of weed seedlings (Jabbour et al. 2014a). However, this weed management strategy may worsen weed problems over time if weeds are allowed to set seed (Norris 1999). Conversely, farmers with a longer-term weed-seedbank focus attempt to prevent weeds from setting seed (Jabbour et al. 2014a). Additionally, direct weed control may be avoided through use of mulch. Each of these approaches may form the basis of a farmer’s management philosophy (B Brown, ER Gallandt, unpublished data). However, strategies may also be selected to achieve field- or crop-specific management goals, since each strategy likely represents different effects on the weed seedbank, edaphic organisms, and the relative mix of soil-aggrading versus soil-degrading practices employed.

Seedling-focused management often prioritizes control events during the “critical period,” when crops are most sensitive to competition and weed-free

conditions should be maintained to avoid yield losses (Nieto et al. 1968). Such an approach has been used to maximize efficiency of in-season weed management (Knezevic et al. 2002). If weeds are only controlled in the critical period, later-emerging weeds may proliferate, which may provide benefits resulting from increased biodiversity (Amaral et al. 2016; Crowder and Jabbour 2014), but since these weeds will likely set seed, control costs will likely increase in subsequent crops (Norris 1999).

An alternative to seedling-focused weed management involves a longer-term, seedbank-focused perspective. Many weed species have seed longevity “half-lives” of less than 1 yr (Roberts and Feast 1972). Thus, preventing seed rain causes a rapid decrease in the weed seedbank, which may provide a labor savings in succeeding years (Norris 1999). Therefore, a “zero seed rain” approach uses frequent soil disturbance to minimize credits to the weed seedbank while maximizing debits (Forcella 2003; Gallandt 2014). However, bare soil and frequent disturbance may negatively affect soil health (Browning et al. 1944; Rasmussen 1999).

Farmers may substitute cultivation for weed suppression by mulch. Black polyethylene mulch is

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* First and second authors: Graduate Student and Professor, School of Food and Agriculture, University of Maine, Orono, ME 04469. Corresponding author’s E-mail: bryan.brown@maine.edu

common due to its ability to warm the soil and promote early yield of crops like tomatoes (*Solanum lycopersicum* L.) (Schonbeck and Evanylo 1998a). Polyethylene mulch can reduce the amount of required irrigation (Abu-Awwad 1999) and conserve soil nitrate (Schonbeck and Evanylo 1998b). Natural mulches, such as straw or hay, may also be used to suppress weed growth (Teasdale and Mohler 2000) and improve water infiltration (Shock et al. 1999; Tindall et al. 1991), increase earthworm populations, and replace seasonal carbon and nitrogen losses (Schonbeck and Evanylo 1998b). In some cases, polyethylene and natural mulches may reduce insect and disease damage to crops (Hill et al. 1982; Larentzaki et al. 2008; van Toor et al. 2004), but higher soil moisture and residue levels may also increase incidence of disease (Govaerts et al. 2007).

While each of these alternative weed management strategies may provide adequate crop yields, they represent trade-offs in agroecological effects. Our aim was to characterize multiple dimensions of these fundamentally different weed management strategies to provide farmers with improved understanding of which strategy or combination of strategies best matches their management goals. Economic performance of the systems (B Brown, ER Gallandt, AK Hoshide, unpublished data) and a related case-study narrative (B Brown, ER Gallandt, unpublished data) will be presented elsewhere.

Materials and Methods

Field experiments comparing several contrasting weed management strategies were conducted at the University of Maine Rogers Farm in Old Town, ME (44.93°N, 68.70°W) in 2014 and 2015 on separate fields, both Nicholville very fine sandy loam. Yellow storage onion ('Cortland,' Johnnys Selected Seeds, Winslow, ME) was used as the test crop, since it is commonly grown using each strategy and onion is highly sensitive to weed competition (Ware and McCollum 1975), which makes it a sensitive assay species to evaluate the effectiveness of each management system. Weather conditions during the study were typical for the region (data from www.ncdc.noaa.gov). Average temperature was 16.9 and 17.2 C, and total precipitation was 380 and 473 mm for the growing periods of 2014 and 2015, respectively (Supplementary Figure 1).

Our broad aim was to compare seedling-, seed-, and mulch-based weed management approaches. Ultimately, we chose six systems, described in detail

in the following sections. Literature review and extensive interviews with farmers who have specialized in each weed management strategy (B Brown, ER Gallandt, unpublished data) were used to ensure that each strategy was implemented in a realistic manner.

Critical Period Weed Control. Weeding events were performed about every 2 wk for the duration of the critical period (Table 1). The critical period for direct-seeded onions is the first 8 to 12 wk following emergence (Brewster 2008; Menges and Tamez 1981; Wicks et al. 1973). Since the onions were transplanted, we used an 8-wk critical period in 2014. However, yield loss in 2014 indicated the period was not long enough. In 2015, the critical period duration was adjusted as described by Knezevic et al. (2002), which extended it from 56 d in 2014 to 78 d in 2015.

Zero Seed Rain. For this strategy, beds and paths were weeded about every 2 wk throughout the growing period (Table 1) with a goal of completely preventing weed seed inputs to the seedbank.

Polyethylene Mulch. Embossed black polyethylene mulch 1.2-m wide and 0.025-mm thick (FedCo Seeds, Waterville, ME) was applied with a mechanical applicator (Model 385PL, Bartville Welding Shop, Christiana, PA) prior to transplanting. Transplanting slits were 5-cm wide and were made with a trowel. Weeds in planting holes were hand pulled several times, while paths were cultivated more frequently (Table 1).

Polyethylene Mulch with Straw-Mulched Paths. Mulch was applied and beds were weeded in the same manner as above. Before planting, oat (*Avena sativa* L.) straw was applied to the paths at a rate of 20 Mg ha⁻¹ (Schonbeck 1998). Weeds and volunteer oat emerging through the straw required hand pulling (Table 1).

Straw Mulch. Oat straw was applied more than 1 mo after transplanting (Table 1) to allow time for the soil to warm and for onions to grow large enough to withstand the disturbance of mulching. Straw was applied by hand at a rate of 20 Mg ha⁻¹ (Schonbeck 1998). Straw was spread quickly in the paths, but in the beds it was carefully laid in bundles around the onions. Three to four weeding events were necessary prior to mulch application (Table 1). After the mulch was applied, one hand-pulling event was necessary to control weeds and volunteer oat.

Table 1. Schedule of field operations for six organic weed management strategies tested in Old Town, ME, in 2014 and 2015.

Year	Weed management strategy	Date					
		Planting	Mulching	Weeding	Harvest	Onion curing	
2014	Critical period	May 13	—	May 29, June 9, 19, 27, July 3	September 18	September 24–October 20	
	Zero seed rain	May 13	—	May 29, June 9, 19, 27, July 3, 10, 30, August 12, 26	September 10	September 13–27	
	Polyethylene mulch	May 13	May 12	Beds (June 9, 19, July 10) Paths (May 29, June 9, 19, 27, July 10)	August 27	August 29–September 12	
2015	Polyethylene mulch, straw paths	May 13	May 12	June 9, 19, July 10	August 27	August 29–September 12	
	Straw mulch	May 13	June 24–Jul 1	May 29, June 9, 19, 24, July 30	September 18	September 24–October 20	
	Hay mulch	May 13	June 24–Jul 1	May 29, June 9, 19, 24, July 30	September 18	September 24–October 20	
	Critical period	May 18	—	June 4, 17, 30, July 14, 30	September 28	September 29–October 26	
	Zero seed rain	May 18	—	June 4, 7, 30, July 14, 30, August 11, 20, September 10	September 28	September 29–October 26	
	Polyethylene mulch	May 18	May 14	Beds (June 22, July 14, August 11) Paths (June 17, 30, July 14, 30, August 14)	September 10	September 12–29	
2015	Polyethylene mulch, straw paths	May 18	May 14	June 17, July 14, August 11	September 10	September 12–29	
	Straw mulch	May 18	July 2	June 4, 17, 30, August 11	September 28	September 29–October 26	
	Hay mulch	May 18	July 2	June 4, 17, 30, August 12	September 28	September 29–October 26	

Hay Mulch. Decaying timothy (*Phleum pratense* L.) hay, not suitable for horses, was obtained locally. Hay was applied and managed in the same manner as the straw mulch (Table 1).

Experimental Design. Each of the six weed management systems was implemented as a treatment in a randomized complete block design with four replicates. Each plot was 6.1-m long by 1.7-m wide. To ensure consistent competition and edge effects, a buffer bed of onions was transplanted on either side of each plot, and blocks were separated by an unplanted area of 2.4 m.

Field Preparation. Primary and secondary tillage were conducted using a rototiller and field cultivator, respectively. Preplanting fertilizer was applied based on soil test recommendations prior to secondary tillage. In 2014, 1,483 kg ha⁻¹ soybean meal (7.0-0.5-2.3, FedCo Seeds, Waterville, ME), 908 kg ha⁻¹ composted poultry litter (3-2-3, MicroStart 60, Perdue Agribusiness, Salisbury, MD), 454 kg ha⁻¹ bone char (0-16-0, FedCo Seeds, Waterville, ME) provided 131-98-61 kg ha⁻¹ (N-P-K). In 2015, 1,337 kg ha⁻¹ soybean meal, 1,110 kg ha⁻¹ dehydrated poultry litter, and 441 kg ha⁻¹ bone char provided 127-100-64 kg ha⁻¹ (N-P-K). All materials were measured and applied by hand.

Planting. Onions were started in late February in a heated greenhouse. Flats containing an organic potting mix (Light Mix, Living Acres, New Sharon, ME) were planted with 500 seeds per flat. In the period prior to transplanting, seedlings were fertilized three times with fish hydrolysate (2.9-3.5-0.3, FedCo Seeds, Waterville, ME) diluted to 1% concentration. Transplanting was done by hand in May (Table 1), following tillage and polyethylene mulch application. To reduce transplant shock, onion tops were trimmed to 13 cm the day prior to planting. Onions were bare-root transplanted with roots trimmed to 3 cm. Transplanting was done by block. Each plot contained one bed of three onion rows, with rows spaced 30-cm apart, planting holes 15-cm apart, and two onions per hole. An additional 408 kg ha⁻¹ fish hydrolysate was applied immediately following transplanting.

Weed Management. Paths were weeded with wheel hoes, long-handled hoes were used closer to crop rows, short-handled hoes were used in the crop row, and hand pulling was only necessary for mulched plots. Buffer beds were unmulched and weeded

every 2 wk throughout the season. Weed-free subplots 2.0-m long by 1.7-m wide were established within each main plot and were weeded at least weekly to ensure that weed competition did not affect yield.

Irrigation. Optimal soil moisture was maintained for each strategy using drip irrigation (Triple K Irrigation, Morenci, MI) with 16-mm-diameter emitters spaced every 30 cm, each with an output of 19 cc min⁻¹. Irrigation was set up prior to transplanting, with one line per bed. Lines were laid on top of the soil by hand. Mulches were applied on top of irrigation lines. Soil water-holding capacity was determined by examining soil moisture over time after a heavy rain. To estimate the amount of irrigation needed to recharge the surface water deficit, volumetric soil moisture was measured weekly with a Delta-T HH2 Soil Moisture Meter with a 5.1-cm Theta Probe (Delta-T Devices, Burwell, UK) at four surface locations in each plot.

Data Collection. Effects of each weed management system on weeds, yield, and other variables were measured to comprehensively characterize each system.

Weeds. The percent of the ground covered with weeds was estimated visually at two random locations in the bed and two random locations in the paths of each plot using a 0.25-m² quadrat. These assessments occurred regularly through the season at 7 and 16 dates in 2014 and 2015, respectively. End-of-season aboveground weed biomass was measured within 1 d of harvest using a 0.25-m² quadrat placed randomly in the bed and randomly in the paths of each plot. Within the quadrat, all weeds were clipped at the soil surface and separated by species. Samples were placed in drying ovens for 1 wk at 46 C, and dried samples were weighed. Weed seeds were threshed from the dried weed samples and weighed. The total number of weed seeds was found by dividing the total seed mass of each species by the average mass of a single seed. Dried weeds and seeds were returned to their respective plots in November of each year, prior to snowfall. To evaluate the amount of weed seed in the organic mulches, in July of each year, four 100-g samples of each mulch were spread in a thin layer on flats of sterile potting mix (Pro-Mix[®] All Purpose Mix, Premier Tech, Quebec, Canada) and covered with a 1-cm layer of potting mix. Flats were watered regularly for 1 mo to

encourage germination. Emerged seedlings were identified, recorded, and removed.

Early-Season Onion Leaf Length. Early-season onion leaf length was determined based on the average length of the longest leaf of four randomly chosen onions per plot on June 27, 2014, and July 9, 2015.

Yield. Onions were harvested at 70% “tops-down” on a per treatment basis. Harvest occurred in a 1-m by 1-m quadrat centered on the bed in a random location within each main plot and each weed-free subplot. Harvested onions were laid in a single layer on wire tables in a ventilated greenhouse to cure. Treatments harvested later in the season required a longer curing duration (Table 1), likely due to decreased temperature and decreased light intensity. Once all onion tops had dried to a brown papery state, roots and loose scales were removed, tops were cut 1 cm above the folding point in the neck, and onion bulbs were weighed. Visibly diseased onions were not included in yield data. Diseases were diagnosed by plant pathologist Jianjun Hao (School of Food and Agriculture, University of Maine).

Onion Storability. In December of each year, following an autumn cooling period in an unheated barn, four marketable onions from each plot were randomly selected to be stored in a walk-in cooler at 1.7 C and 75% relative humidity. The 2014 and 2015 onions were removed from cold storage May 19, 2015, and July 15, 2016, respectively. Firmness was tested using a Brookfield LFRA Texture Analyzer (Brookfield Ametek, Middleboro, MA) running at 4 mm sec⁻¹ with a 5-cm-diameter acrylic compression head. When the head confronted an 8-g trigger it measured peak pressure required to continue for 1.5 mm. Onion pH and soluble solids were measured using an Orion Star A211 pH Meter (Thermo Fisher Scientific, Waltham, MA) and an Atago rx-5000i Refractometer (Atago U.S.A., Bellevue, WA), respectively, using blended samples from each plot.

Soil Temperature. Throughout the field experiments, soil temperature was measured at a depth of 5 cm once per week in the midafternoon using an Omega Model HH21 Microprocessor Thermometer with a Hanna Type K Thermocouple (Omega Engineering, Stamford, CT).

Carabid Beetles and Earthworms. Activity-density of granivorous carabid beetles (family Carabidae),

including genera *Amara*, *Bembidion*, *Clivina*, *Harpalus*, *Poecilus*, and *Pterostichus*, was measured by installing one pitfall trap in a random location in the bed of each plot using methods adapted from Birthisel et al. (2014). A 30-cm slit was cut in the polyethylene mulch treatments to facilitate installation. Traps were examined four times in 2014 and twice in 2015, with 24- to 48-h catch time for each event, all in early August. Results demonstrated carabid habitat preference, but due to relatively small plot sizes, high activity-density of some plots may correspond with a decrease in activity-density of other plots. Earthworm (phylum Annelida) abundance was measured by excavating a 15-cm by 42-cm by 20-cm volume between onion rows in each plot in late August, and sifting samples following Edwards and Lofty (1977).

Invertebrate Pests and Disease. Onion thrips (*Thrips tabaci* Lind.) populations were measured weekly in 2014 using a hand lens to count the thrips on eight random onion plants per plot. In 2015, the destructive sampling method of Larentzaki et al. (2008) was adopted, in which 1 onion plot⁻¹ was removed and placed in a bag with 200 ml of 65% ethyl alcohol, agitated for 1 min, and poured into a 200- μ m micron sieve to count dislodged thrips. The revised method was implemented once in June, July, and August. An action threshold of 3 thrips per leaf was not attained in either year. Additionally, in 2015, plots were examined for other arthropod and disease damage by four field-scouting events in August.

End-of-Season Soil Quality. In late August of each year, several soil-quality measurements were conducted. Soil samples collected to a depth of 15 cm from 10 random locations within the bed of each plot were analyzed for nitrate, ammonium, and microbial biomass by the University of Maine Soil Testing Service. In addition, soil water-infiltration rate was measured by recording the time required for 1 L water to soak into pre-wetted soil inside a 20-cm-diameter aluminum cylinder that had been inserted 8 cm into the soil (Anderson and Ingram 1989). Depth to compaction was measured at four locations per plot using a penetrometer with a 1-cm tip that was inserted to a resistance of 2.1 Mpa (Duiker 2002), which was enough compaction to severely impair root growth (Bengough and Young 1993). Since soil moisture may affect penetrometer results (Hummel et al. 2004), measurements were taken 24 h after irrigation, when soil was uniformly at water holding capacity (Duiker 2002).

Legacy Effects of Treatment. In September 2014 and 2015, after all onions had been harvested, fields were rototilled, which typically causes minimal horizontal movement of weed seeds (Grundy et al. 1999), and oats ('Aroostook,' Johnnys Selected Seeds, Winslow, ME) were planted with a 3-m grain drill (Massey Ferguson, Duluth, GA) with 15-cm row spacing at a rate of 224 kg ha⁻¹. In May 2015, prior to incorporation of oats, soil organic matter was tested from a homogenized sample of 10 soil cores per plot, to a depth of 15 cm. Immediately following soil sampling, oats were incorporated by rototilling and field cultivating.

In 2015 only, sweet corn ('Xtra-Tender 3473,' Johnnys Selected Seeds, Winslow, ME) was planted on June 4 with rows spaced 81-cm apart and plants 20-cm apart within rows. In this spacing, two rows were centered within the bounds of the previous year's plots. Most fertilizer (1,318 kg ha⁻¹ soybean meal, 412 kg ha⁻¹ composted poultry litter, and 165 kg ha⁻¹ bone char) was applied prior to secondary tillage, and additional fertilizer (659 kg ha⁻¹ composted poultry litter and 329 kg ha⁻¹ fish hydrolysate) was side-dressed on July 10, providing a total of 134-66-63 kg ha⁻¹ (N-P-K). To protect the corn from crows, plots were covered with spun-bonded polypropylene (Agribon, San Luis Potosi, Mexico) until the corn was in the 3-leaf stage. The corn was managed uniformly across all previous treatments. Weed control consisted of a spring tine harrowing (Lely Industries NV, Series 982, Type 3, Maasland, Holland) on June 15; interrow cultivations with a 4-row Case International Model 183 (Case IH, Racine, WI) with Danish S-tines and 10-cm sweeps and gauge wheels on June 15, June 25, and July 7; and disk hillings (Weedmaster, Elomestari Oy, Kukkola, Finland) on June 25 and July 10. In addition to the field-wide cultivations, weed-free subplots were maintained by hand weeding on June 19, July 6, July 20, July 31, and August 12. Harvest of first ears occurred on August 24 and second ears on September 2. Entire plots were harvested for yield data. Yield was defined as the fresh mass of ears from both harvests. Corn earworm (*Helicoverpa zea* Boddie) damage was evaluated in 10 ears plot⁻¹ on the second harvest date. Immediately following harvest, end-of-season aboveground weed biomass was sampled in the same manner as for the onions.

Statistical Analyses. All analyses were completed using JMP 10 (SAS Institute, Cary, NC). ANOVA was used to determine effects of weed management

strategy on dependent variables. Due to several important Year*Treatment interactions, years were analyzed separately. Fisher's protected LSD was used for means comparisons unless otherwise stated. An alpha level of 0.05 was used throughout. Data failing to meet assumptions for ANOVA were subjected to log, square-root, or Box-Cox (Box and Cox 1964) transformations as necessary. Data unable to pass assumptions after transformations were analyzed with the nonparametric Kruskal-Wallis test (Kruskal and Wallis 1952). Pairwise Wilcoxon signed-rank tests (Wilcoxon 1945) were used for means comparisons as appropriate. If an effect of strategy was present in onion yield of weed-free subplots, edaphic variables that were affected by system were evaluated as main effects in a multiple linear regression model of onion yield. Stepwise backward selection was used to eliminate nonsignificant variables, followed by evaluation with adjusted R² and Akaike information criterion with correction for finite sample sizes (Akaike 1974). To evaluate the effects of strategy on subsequent crops, orthogonal contrasts were used to evaluate weed biomass and sweet corn yield of the critical period system versus all others.

Results and Discussion

In-Season Effects of Weed Management Strategy.

As will be discussed, the six weed management strategies in this experiment varied in their effectiveness, as demonstrated through weed control and onion yield. But they also differed in effects on soil health, edaphic invertebrates, and implications for subsequent crops.

Weeds. The most abundant weed species included common lambsquarters (*Chenopodium album* L.), smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.], and low cudweed (*Gnaphalium uliginosum* L.). The percent of the ground area covered by weeds fluctuated based on timing of weeding events (Figure 1). But for the critical period system, weed cover sharply increased at the end of the season, reflecting uncontrolled weed growth in late July, August, and early September. The reduction in weed cover in 2015 compared with 2014 was expected, because we extended the weeding period in that year. Likewise, end-of-season weed biomass was greatest in the critical period system in both years, but was reduced by 41% in 2015 (Table 2). Weed biomass was least in the zero seed rain, straw mulch, and hay mulch treatments, commensurate

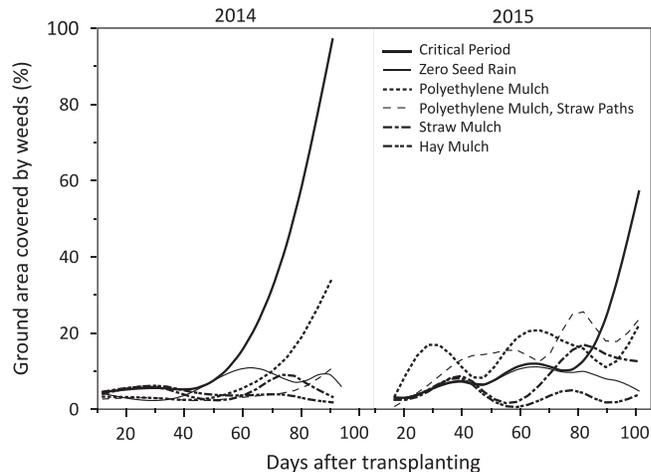


Figure 1. Ground area covered by weeds for each weed management system at 7 and 16 dates in 2014 and 2015, respectively. Mean weed cover of the beds and paths of each system were plotted by date and smoothed with a cubic spline ($\lambda = 0.05$).

with the increased labor required for those systems (B Brown, ER Gallandt, AK Hoshide, unpublished data). Comparatively, polyethylene-mulched plots had greater weed biomass, likely due to the infrequent weeding events, as well as the difficulty controlling weeds emerging from the planting holes and the margins of the polyethylene. Smaller planting holes would likely have reduced weed emergence but increased labor costs associated with hand transplanting (B Brown, ER Gallandt, AK Hoshide, in review). The apparent increase in weed cover (Figure 1) and biomass (Table 2) in the polyethylene systems from 2014 to 2015, may relate to presence

Table 2. Effects of weed management strategy on end-of-season aboveground weed biomass and weed seed production.^a

Weed management strategy	End-of-season aboveground weed biomass ^b		Weed seed production ^c	
	2014	2015	2014	2015
	g m ⁻²		no. m ⁻²	
Critical period	619 a	367 a	29,042 a	21,675 a
Zero seed rain	7 c	8 c	0 c	57 d
Polyethylene mulch	97 b	117 b	787 b	5,277 b
Polyethylene mulch, straw paths	110 b	161 ab	1,267 b	4,515 b
Straw mulch	10 c	20 c	27 c	285 cd
Hay mulch	15 c	16 c	19 c	599 c
ANOVA	P			
Strategy	<0.001	<0.001	<0.001	<0.001

^a Data were collected immediately after onion harvest in 2014 and 2015. Within each column, means followed by the same letter are not significantly different.

^b Means separated using Fisher's protected LSD test at $P \leq 0.05$.

^c Box-Cox transformed for ANOVA and Fisher's protected LSD test at $P \leq 0.05$. Reported values untransformed.

of more monocotyledonous weeds (unpublished data), which were more challenging to remove from planting holes (Figure 1).

As expected, weed seed production was greatest for the critical period treatment and close to zero in the zero seed rain system (Table 2). Average weed seed production of the critical period systems was 25,359 seeds m^{-2} . Indeed, while the majority of organic vegetable farms evaluated in New England had less than 10,000 seeds m^{-2} (Jabbour et al. 2014a), one farmer who often follows the critical period strategy had a germinable weed seedbank of nearly 40,000 seeds m^{-2} (B Brown, ER Gallandt, unpublished data).

Seeds were also imported in the natural mulches. Germinable seed assays showed that the oat straw mulch contained a large amount of oat seed (contributing 711 germinable seeds m^{-2} , mostly oats), even though it was baled after oat harvest. In the field, oat seed was able to germinate and emerge from within the mulch, which required extra weed management and likely affected onion yield. In contrast, hay mulch included 991 germinable seeds m^{-2} , but in the field, very few weeds were able to emerge through the mulch (Figure 1). Similarly, weed seeds imported by hay mulch were not problematic in organic tomato production (Schonbeck 1998).

Yield. Onion yield varied by system in 2014, with zero seed rain and natural-mulched systems giving the greatest yields (Table 3). Compared with the hay mulch system, polyethylene mulching and critical period treatments demonstrated a yield loss. Onion yield in weed-free subplots also varied by strategy in 2014, with polyethylene-mulched treatments

yielding the least, possibly due to higher soil temperatures (Figure 2), which accelerated early-season leaf growth (Table 3; also observed by Anisuzzaman et al. 2009) and likely contributed to premature senescence and early harvest (Table 1). However, in 2015, onion yields were similar across strategies in main plots and weed-free subplots (Table 3). This result reflects the lengthened weed control period (Table 1) for the critical period treatment and reduced soil temperatures (Figure 2), which may have allowed more bulbing time before senescence and harvest (Table 1). Lack of statistical differences between systems may also relate to high variability in yield (Table 3), which may reflect the relatively small sample sizes.

In our related economic analysis, onion yield was more important than labor and materials costs in determining profitability in an enterprise budget for small-scale organic onion production (B Brown, ER Gallandt, AK Hoshide, unpublished data). The two highest-yielding systems, zero seed rain and hay mulch, were most profitable despite incurring the greatest weeding labor and total labor costs, respectively. Mulched systems were less risky than cultivated systems, reflecting less variable yields (Table 3).

After harvest, onions with apparent defects were evaluated for disease. Diseases included black mold (*Aspergillus niger* Tiegh.), bacterial soft rot (*Dickeya chrysanthemi* (Samson et al. 2005)), and blue mold (*Penicillium* spp.); however, disease incidence was very low and not affected by weed management strategy.

Following cold storage, soluble solids levels, indicative of onion sugars and storability (McCallum et al. 2006), were greatest in the highest-yielding

Table 3. Effects of weed management strategy on early onion growth and yield in 2014 and 2015.^a

Weed management strategy	Early-season leaf length ^b		Yield ^b		Weed-free yield	
	2014	2015	2014	2015	2014 ^c	2015 ^b
	cm		Mg ha ⁻¹		Mg ha ⁻¹	
Critical period	29 b	34 bc	34.6 (21.8–47.4) c	47.7 (24.3–71.1)	53.1 (49.9–56.3) c	55.2 (38.5–72.0)
Zero seed rain	27 bc	33 c	52.5 (33.1–71.9) ab	58.2 (45.7–70.7)	51.7 (44.0–59.4) abcd	55.3 (38.1–72.5)
Polyethylene mulch	35 a	43 a	42.5 (35.3–49.7) bc	52.7 (40.0–65.3)	43.0 (21.3–64.6) bcd	56.5 (30.8–82.2)
Polyethylene mulch, straw paths	35 a	44 a	47.4 (40.7–54.1) b	44.9 (36.8–53.1)	48.5 (45.1–51.8) d	58.4 (30.9–85.8)
Straw mulch	29 b	38 b	51.9 (39.4–64.4) ab	46.7 (36.2–57.2)	64.3 (56.9–71.7) a	63.2 (54.4–72.0)
Hay mulch	24 c	35 bc	60.5 (51.7–69.2) a	53.6 (48.5–58.8)	58.6 (54.2–63.0) ab	52.0 (40.2–63.9)
ANOVA				P		
Strategy	<0.001	<0.001	0.003	0.184	0.009	0.660

^a Within each column, means followed by the same letter are not significantly different. Yield data are presented with 95% confidence intervals in parentheses.

^b Data were untransformed for ANOVA. If significant, means were separated using Fisher's protected LSD test. Both tests were conducted at $P \leq 0.05$.

^c Main effects tests performed with Kruskal-Wallis tests and means comparisons performed with Wilcoxon paired tests, both at $P \leq 0.05$.

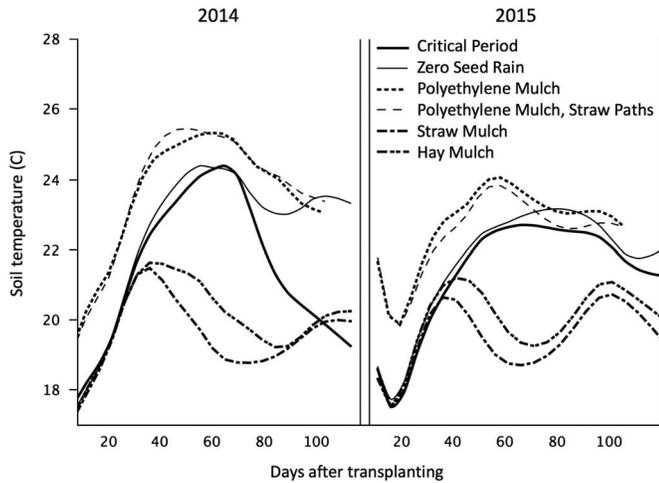


Figure 2. Afternoon soil temperature measured at a depth of 5 cm for each weed management strategy in 2014 and 2015. Each line represents weekly afternoon soil temperature readings smoothed with a cubic spline ($\lambda = 0.05$). Readings were discontinued after harvest of each treatment.

treatments of 2014 (Table 4). Onion firmness, a desirable postharvest trait (Larsen et al. 2009), was greatest in unmulched systems in 2014 (Table 4). However, these onion-quality parameters were not affected by treatment in 2015. Onion pH, sprouting, mold, and rot were also examined but were unaffected by weed management strategy (unpublished data).

Soil Temperature. Soil temperature was greatest under black polyethylene mulch (Figure 2), consistent with Hill et al. (1982). Late in the season, soil temperatures in the zero seed rain system

Table 4. Effects of weed management strategy on onion bulb firmness and soluble solids after a period of cold storage.^a

Weed management strategy	Bulb firmness		Soluble solids	
	2014 ^b	2015 ^d	2014 ^b	2015 ^c
	kg		degrees Brix	
Critical period	3.3 ab	2.5	6.6 c	7.3
Zero seed rain	3.5 a	2.5	7.6 a	7.2
Polyethylene mulch	2.6 c	2.5	6.7 c	7.4
Polyethylene mulch, straw paths	2.7 c	1.9	6.9 bc	7.1
Straw mulch	2.9 bc	2.2	7.4 ab	6.8
Hay mulch	2.7 c	2.5	7.7 a	7.1
ANOVA		P		
Strategy	0.011	0.614	0.008	0.948

^a Within each column, means followed by the same letter are not significantly different.

^b Means separated using Fisher's protected LSD test at $P \leq 0.05$.

^c Log transformed for ANOVA at $P \leq 0.05$. Reported values untransformed.

^d Main effects tests performed with Kruskal-Wallis tests at $P \leq 0.05$.

approached those of polyethylene-mulched systems, likely due to the soil remaining unshaded by weeds. Conversely, soil temperature in the critical period system dropped as late-season weeds emerged. Soil temperature in natural-mulched plots cooled after mulch was applied, as reported elsewhere (Teasdale and Mohler 1993).

Irrigation. Soil moisture was maintained optimally for each strategy by drip irrigation. In 2014, the critical period and zero seed rain treatments received 5,600 cc water m^{-2} , while polyethylene and natural-mulched plots required 13% less irrigation. In 2015, the zero seed rain system required the most irrigation (11,000 cc m^{-2}), while the critical period, straw mulch, hay mulch, polyethylene mulch, and polyethylene mulch with straw paths treatments required 11%, 20%, 22%, 45%, and 47% less water, respectively.

Carabid Beetles and Earthworms. Activity-density of carabid beetles, including *Harpalus rufipes* Deg., a well-known seed predator (Gallandt et al. 2005), was greatest in the critical period system (Table 5), possibly due to the habitat provided by weeds, but activity-density was least in the natural mulch systems. Indeed, weed seed predation has been positively correlated with living vegetative cover but negatively correlated with residue (Birthisel et al. 2015), possibly due to hindrance of carabid mobility (Thomas et al. 2006). Earthworms were more abundant in natural-mulched systems (Table 5), as found by Schonbeck and Evanylo (1998b). Earthworms are generally beneficial for increasing soil

Table 5. Effects of weed management strategy on beneficial invertebrates in 2014 and 2015.^a

Weed management strategy	Carabid activity-density		Earthworms	
	2014	2015	2014	2015
	no. trap ⁻¹		no. m^{-2}	
Critical period	21 a	42 a	24 b	112 bc
Zero seed rain	3 cd	9 c	20 b	60 c
Polyethylene mulch	8 b	25 b	8 b	64 c
Polyethylene mulch, straw paths	5 bc	17 b	24 b	52 c
Straw mulch	2 d	4 c	104 a	164 ab
Hay mulch	1 d	7 c	108 a	184 a
ANOVA		P		
Strategy	<0.001	<0.001	<0.001	0.002

^a Measurements were conducted in August of each year. Within each column, means followed by the same letter are not significantly different. Means separated using Fisher's protected LSD test at $P \leq 0.05$.

Table 6. Effects of weed management strategy on four measures of soil quality in 2014 and 2015.^a

Weed management strategy	Depth to compaction ^b		Nitrate ^c		Microbial biomass ^b	
	2014	2015	2014	2015	2014	2015
	cm		mg kg ⁻¹		mg kg ⁻¹	
Critical period	29 bc	24	4 d	8 c	56 a	51
Zero seed rain	27 c	31	9 c	25 bc	49 b	56
Polyethylene mulch	41 a	31	63 a	110 ab	47 b	37
Polyethylene mulch, straw paths	39 a	35	121 a	114 a	48 b	42
Straw mulch	37 ab	27	9 c	13 c	58 a	55
Hay mulch	35 ab	34	17 b	6 c	55 a	46
ANOVA	P					
Strategy	0.008	0.116	<0.001	0.004	0.006	0.166

^a Within each column, means followed by the same letter are not significantly different.

^b Means separated using Fisher's protected LSD test at $P \leq 0.05$.

^c Box-Cox transformed for ANOVA and Fisher's protected LSD test at $P \leq 0.05$. Reported values untransformed.

humus and aeration (Edwards and Lofty 1977; Hopp and Hopkins 1946).

Invertebrate Pests and Disease. Invertebrate pests and onion diseases included onion thrips, onion maggot (*Delia antiqua* Meigen), cutworm species (family Noctuidae), saltmarsh caterpillar (*Estigmene acrea* Drury), and purple blotch (*Alternaria porri* Ellis), but occurrence was highly variable and not affected by weed management system (unpublished data).

End-of-Season Soil Quality. End-of-season soil quality was generally most favorable for the mulched treatments (Table 6). Penetrometer tests measuring soil compaction varied by strategy in 2014, with mulched plots demonstrating less compaction, possibly due to decreased soil crusting (Schonbeck 2012) or improved soil aggregation (Tindall et al. 1991). Water-infiltration rate, a measure expected to be inversely related to compaction, was not affected by strategy in 2014 [$F(5,15) = 1.65$, $P = 0.206$] or 2015 [$F(5,15) = 0.773$, $P = 0.584$]. Soil nitrate was greatest in polyethylene-mulched systems in both years, a result observed elsewhere in the literature (Schonbeck and Evanylo 1998b), possibly due to decreased leaching in heavy rains or due to higher soil temperature causing increased mineralization (Waggoner et al. 1960). Ammonium was also tested but did not differ by strategy (unpublished data). Microbial biomass, an indicator of soil health, was greatest in critical period and natural-mulched treatments in 2014, likely due to the reduced late-season soil disturbance and higher residue of these treatments (Islam and Weil 2000). It is unclear why the polyethylene-mulched treatments did not also demonstrate increased microbial biomass.

Soil-Quality Effects on Yield. In 2014, onion yield in weed-free conditions was affected by weed management strategy (Table 3). To investigate which factors, other than weeds, affected yield, a linear regression model of onion yield was created with select soil-related main effects (Table 7). The model was reduced to earthworm abundance and mean soil temperature. Earthworms may have positively affected yield due to their previously discussed effects on soil quality. Soil temperature was likely related to the early senescence of onions in the black polyethylene-mulched systems. Indeed, in Maine, lighter-colored polyethylene mulches are beginning to be used to avoid causing premature onion senescence (J Kafka and R Johanson, personal communication).

Legacy Effects

Soil Organic Matter. In May of 2015, following the initial onion crop, residue from the natural mulches was still evident despite rototilling and

Table 7. The significance of soil-related parameters on the onion yield of main plots in 2014.

Soil-related parameter	Full model	Reduced model ^a
	P	
Mean soil temperature	0.231	0.139
Earthworms	0.028	0.008
Compaction	0.802	—
Soil nitrate	0.884	—
Microbial biomass	0.755	—
Model performance		
$P > F$	0.127	0.011
Adjusted R ²	0.179	0.290
AICc	521.9	511.2

^a Stepwise backward elimination of least significant parameters was used to reduce the model based on the adjusted R² and Akaike information criterion with correction (AICc) for finite sample sizes (Akaike 1974).

winter cover cropping. However, soil organic matter analyses did not indicate any difference between weed management strategies [$F(5,15) = 1.09$, $P = 0.405$]. It is expected that long-term use of natural mulches would increase soil organic matter. From our related case studies, one mixed-vegetable grower using natural mulches for many years now has soil organic matter over 20% and has reduced fertilizer input (B Brown, ER Gallandt, unpublished data).

Effects on Subsequent Crop Yield. Yield of sweet corn in weed-free subplots did not differ by strategy in the year following onions ($F(5,15) = 1.28$, $P = 0.323$). This indicates that a single year of each weed management strategy did not affect soil quality enough to affect yield of the following crop. In main plots, where weed control was achieved with tractor cultivation but no hand weeding, former critical period plots resulted in 685 g m^{-2} of aboveground weed biomass, likely related to increased seed production from the previous year (Table 2), while the other plots had less weed biomass [$F(1,15) = 27.1$, $P < 0.001$], with a mean of 117 g m^{-2} . Likely related to weed competition, the yield of former critical period plots was 22% less than the other treatments [$F(1,15) = 10.8$, $P = 0.004$], which yielded 16.6 Mg ha^{-1} on average. It is also possible that the reduced end-of-season soil nitrate level in the critical period system (Table 6) contributed to the sweet corn yield loss. Enterprise budgets for the sweet corn operations showed that the yield loss in the plots where the critical period system was implemented the prior year resulted in a loss of over 2,500 USD ha^{-1} compared with the other systems (B Brown, ER Gallandt, AK Hoshide, unpublished data), and it is likely the loss would have been greater in higher-value crops.

Management Implications. In the context of small-scale, organic production of onions, a long-season weed-sensitive crop, the zero seed rain and natural mulching strategies performed favorably in terms of weed control and onion yield. This result reflects the more intensive management involved with these strategies. Unexpectedly, despite incurring the highest labor costs, the zero seed rain and hay mulch systems were most profitable (B Brown, ER Gallandt, AK Hoshide, unpublished data). A key difference was that labor requirements were evenly spread for the zero seed rain system, while labor was concentrated in late June to early July for the hay mulch system (B Brown, ER Gallandt, AK Hoshide, unpublished data). In more weed-tolerant crops that are less responsive to intensive management, it is

likely that the critical period and polyethylene mulching systems, would be more profitable due to reduced costs. Furthermore, these strategies would likely be more feasible than the other strategies on a large scale due to less dependence on hand labor.

In addition to profitability, farmers consider the ecological effects of management (Robertson et al. 2014). Perhaps the most influential ecological effect was the abundant weed seed production of the critical period system (Table 2), which likely affected the subsequent crop. Conversely, weed seed production was least in the zero seed rain, straw mulch, and hay mulch systems, which would likely reduce future weeding costs (Norris 1999). Unfortunately, such preventative, long-term management is less common than seedling-focused management, because growers often believe that weeds are inevitable (DeDecker et al. 2014; Wilson et al. 2015), perhaps due to an overestimation of seed longevity (Jabbour et al. 2014b).

Mulched treatments generally performed favorably in measures of soil health (Table 6). However, materials costs for polyethylene- and natural-mulched systems were around US\$500 and US\$4,000 ha^{-1} greater than cultivated systems, respectively (B Brown, ER Gallandt, AK Hoshide, unpublished data). The straw mulch treatment did not perform to its potential, given the volunteer oats. Perhaps farmers could grow their own straw to ensure seed-free mulch or store bales outdoors for the season prior to application to encourage fatal germination of seeds in the mulch.

Although a single weed management strategy may resonate with a farmer's management "philosophy" (DeDecker et al. 2014), we suggest the strategies presented herein be used based on the management goals for a particular field or crop. While the length of the critical period, the amount of weeding labor required, and the response to mulch may vary by crop, many of the ecological effects of these weed management systems would likely apply to other crops. Furthermore, we have presented each strategy separately, but approaches could be combined to provide multiple benefits. For example, a zero seed rain approach could be used simultaneously with natural mulching to achieve a seedbank reduction while benefiting from the soil-aggrading properties of mulch.

We conclude that each weed management system presents trade-offs in effects on agroecology (Tables 2–6). Therefore, the "best" strategy depends on grower management goals (B Brown, ER Gallandt, unpublished data). It is our aim that this paper clarifies the ecological benefits and drawbacks of each strategy so that growers may adjust their management appropriately.

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Supplementary material

To view supplementary material for this article, please visit <https://doi.org/10.1017/wsc.2017.34>

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