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An economic comparison of weed management systems used in small-scale organic vegetable production

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Abstract Weed management strategies likely provide trade-offs in economic implications. Farmers may prioritize weed control during the "critical period" of the crop and ignore subsequent weeds; they may focus on the long term by eliminating additions to the weed seedbank with a "zero seed rain" approach; or they may suppress weed emergence with polyethylene (PE) or hay mulch. We aimed to compare the economic trade-offs of these approaches by implementing each system in a test crop of yellow onion (*Allium cepa* L.). We found that the zero seed rain system required the most weeding labor and the most evenly spread workload, while the hay mulch system required the most concentrated workload, due to the task of mulching. Despite the labor costs of the zero seed rain and hay mulch systems, net farm income (NFI) was most sensitive to onion yield and these systems resulted in the greatest NFI. The hay mulch system represented the least economic risk, followed by the zero seed rain, PE mulch, and critical period systems, respectively. In a subsequent crop of sweet corn, NFI was decreased 2524 USD ha^{-1} in plots where the critical period system had been implemented the previous year, likely due to increased weed competition. Overall, despite the long-term focus of the zero seed rain and hay mulch systems related to the weed seedbank and soil quality, respectively, these systems were most profitable in this short-term study.

Keywords Critical period · Zero seed rain · Mulch · Enterprise budget · Economic risk · Onion

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Introduction

As organic agriculture expands in response to consumer demand, weed management remains a key challenge (McErlich and Boydston 2013). Current weed management approaches of organic vegetable farmers may be categorized into distinct overarching "philosophies" (DeDecker et al. 2014). Many farmers aim to control weed seedlings, while others focus on depleting the number of weed seeds in the soil (Jabbour et al. 2014) or invest in mulch to suppress weeds (Baker and Mohler 2014). An improved understanding of each approach is critical for farmers to be most successful (Brown and Gallandt 2017b).

Farmers that control weed seedlings may minimize labor by confining weeding events to the "critical period" of the crop, when weed-free conditions are required to avoid yield loss (Nieto et al. 1968;

Knezevic et al. 2002). However, if weeds are only controlled during the critical period, weed seed production is likely (Bagavathiannan and Norsworthy 2012; Brown and Gallandt 2017a), increasing the weed seedbank (Bond et al. 1998) and contributing to increased weed emergence in subsequent crops (Norris 1999).

Alternatively, a "zero seed rain" approach has a more long-term focus on preventing weed seed production and the corresponding "rain" of seeds to the ground (Norris 1999; Gallandt 2014). This approach recognizes that seeds of many weed species are short-lived (Roberts and Feast 1972); therefore, preventing weed seed rain should cause a rapid decrease in the weed seedbank, and labor savings in subsequent years (Norris 1999). Indeed, some large-scale conventional vegetable farms in California have adopted this system to reduce their weed seedbanks, and ultimately, herbicide usage (Norris 1999). Nordell and Nordell (2009) popularized this approach for organic mixed-vegetable growers. After several years of weed seed prevention along with practices that deplete the weed seedbank, they observed a dramatic reduction in weed emergence, which allowed for reduced weeding labor.

A third distinct weed management approach involves the use of mulch to suppress weed emergence. Mulching requires an early-season investment in labor and materials but results in reduced weeding labor later in the season. Polyethylene (PE) film mulch is commonly used to warm the soil and promote early yield of solanaceous (Schonbeck and Evanylo 1998a; Cirujeda et al. 2012) and cucurbitaceous crops (Farias-Larios and Orozco-Santos 1997; Sanders et al. 1999; Kaya et al. 2005). Additionally, the weed suppressive and moisture retaining properties of PE film have allowed it to increase marketable yields in other crops, such as onion (Vavrina and Roka 2000), cabbage (Trdan et al. 2008), and head lettuce (Brault et al. 2002). Natural mulches, such as hay, may also be used to suppress weeds. In organic bell pepper, profitability of production with PE and natural mulches was comparable to local conventional production using herbicides (Law et al. 2006). In organic tomatoes, a hay mulch system reduced weed biomass and, in some site-years, resulted in a net labor savings (Schonbeck 1998), or greater yields compared to cultivated or PE mulch systems (Schonbeck and Evanylo 1998a).

We hypothesized that critical period weed control, zero seed rain management, and mulching with PE or hay would vary in labor requirements and profitability, representing contrasting economic benefits and risks. To test this hypothesis, we implemented each system in a replicated field experiment over two years. Onion was used as a test crop to represent a long-season, weed-sensitive crop, for which weed management is often challenging (Wicks et al. 1973). Unlike controlled experiments that vary a limited number of factors, such systems comparisons aim to contrast whole-system effects and have been used to evaluate alternative production systems in vegetables (Halloran et al. 2005; Chan et al. 2011), small grains (Kolb et al. 2010, 2012), and corn-soybean rotations (Cox et al. 1999; Davis et al. 2012; Caldwell et al. 2014). These studies often utilize enterprise budgets to compare profitability. Additionally, risk analysis may be used to identify systems with less variable profitability, and therefore less risk (Ott and Hargrove 1989; Lu et al. 1999). Sensitivity analysis can determine that the extent profitability is affected by variation in input variables such as fertilizer prices (Ott and Hargrove 1989), seed prices (Lu et al. 1999), and crop yield (Chan et al. 2011). Our aim was to use these economic tools to characterize the profitability, risk, and sensitivity of several weed management systems so that small-scale organic farms may use the results to inform their management decisions.

Methods

We selected four weed management systems (detailed below) based on previous literature (Baker and Mohler 2014; DeDecker et al. 2014; Jabbour et al. 2014) and prevalence in ME, USA. Systems were compared in field experiments conducted in 2014 and 2015 at the University of Maine Rogers Farm in Old Town, ME (44.93° N, 68.70° W). A separate field was used for each year. Both fields were Nicholville very fine sandy loam. Weather was typical for the region throughout the study period, with average temperatures of 16.9 and 17.2 °C and precipitation amounts of 380 and 473 mm for 2014 and 2015, respectively (NOAA 2016). Yellow storage onion (*Allium cepa* L., cv. "Cortland") was used as the test crop. Each system was implemented in a randomized complete block design with four replicates. Plots were 6.1 m long by 1.7 m wide. Buffer plots of the same dimensions were located on either side and a 2.4-m buffer was located on either end.

Treatments

Using a combination of previous literature and interviews with farmers that have specialized in each weed management system (Brown and Gallandt 2017b), we ensured that each system was implemented in a realistic manner:

Critical period weed control In direct-seeded onions, the critical weed-free period is the first 56 to 84 days after emergence (Hewson and Roberts 1971; Wicks et al. 1973; Menges and Tamez 1981). Since our onions were transplanted, a 56-day critical period was used in 2014 (M. Guzzi, personal communication). During this period, hoeing was performed about every 14 days. Due to yield loss in 2014, the 2015 critical period was adjusted using growing degree-days, as described by Knezevic et al. (2002), which extended it from 56 days in 2014 to 78 days in 2015.

Zero seed rain With a goal of preventing all seed rain, these plots were hoed about every 14 days from transplanting until harvesting (Brown and Gallandt 2017b).

Polyethylene mulch Prior to transplanting, we applied embossed, black PE mulch (1.2 m wide, 0.025 mm thick, FedCo Seeds, Waterville, ME) with a one-bed mechanical applicator (Model 385PL, Bartville Welding Shop, Christiana, PA), which is a commonly used design on small farms (D. Colson, personal communication). A 5-cm wide trowel was used to make planting holes. Hoeing was used to control weeds in paths, while hand pulling was used to control weeds emerging through planting holes (Schonbeck 1998). After harvest, PE mulch was removed by hand.

Hay mulch Timothy (*Phleum pratense* L.) mulch hay was applied more than one month after transplanting to allow for adequate soil warming (Schobeck and Evanylo 1998a). Hay was applied by hand at a rate of 20 Mg ha^{-1} (Schonbeck 1998). Hay was spread quickly in the paths, but in the beds, it was carefully laid around the onions. One hand-pulling event was used to control weeds after the mulch was applied (T. Roberts, personal communication).

Additional treatments included a PE mulch system with oat (*Avena sativa* L.) straw mulch in the paths as well as an entirely oat straw mulch system. Unfortunately, the straw, which was purchased for this experiment, contained a large amount of viable oat seed, which germinated and emerged through the mulch (Brown and Gallandt 2017a). Thus, these treatments were not included in this economic analysis.

Field management

In early May of each year, primary and secondary tillage were performed with one pass of a rototiller and one pass of a field cultivator, respectively. Organic sources of fertility were applied prior to secondary tillage in quantities (Online Resource 1) based on soil tests (Online Resource 2). All fertility sources were measured and applied by hand.

Onions were sown in flats of organic potting mix (Light Mix, Living Acres, Inc., New Sharon, ME) in late February in a heated greenhouse. Immediately after tillage and application of PE mulch, onions were bare-root transplanted by hand at a spacing of two onions per planting hole, with holes 15 cm apart and rows 30 cm apart. Diluted fish hydrolysate was applied directly after transplanting (Online Resource 1).

Un-mulched paths between onion beds were weeded with wheel hoes, while long-handled hoes were used closer to crop rows, and short-handled hoes were used in the crop row (E. Gallandt, personal communication). Weeds in mulched areas were pulled by hand. Since plots were small, all laborers were instructed to work at a sustainable pace, commensurate with the pace of work in a larger field. Buffer areas were hoed following the zero seed rain system.

Drip irrigation was used to maintain optimal soil moisture for each system. Irrigation lines (Triple K Irrigation, Morenci, MI) contained 16-mm-diameter emitters, spaced every 30 cm, each with an output of 19 cm^3 min^{-1}. Irrigation was applied weekly with an amount estimated to recharge the water deficit to a depth of 32 cm. The water deficit was determined using a Delta-T HH2 Soil Moisture Meter with a 5.1 cm Theta Probe (Delta-T Devices, Burwell, UK) at four locations in each plot.

Marketable onion yield was measured by harvesting a 1 m by 1 m quadrat, centered on the bed of each plot. Harvest occurred on a per treatment basis when 70% of the onion leaves had folded. Harvested onions were laid out to cure on mesh tables in a ventilated greenhouse for several weeks. Visibly unmarketable onions accounted for only 0.6% of the total and were removed from the curing process. After curing, onion leaves and roots were pruned and onions were weighed to determine marketable yield.

In 2015 only, sweet corn (*Zea mays* L. cv. Xtra-Tender 3473) 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 previous year's plots. Fertility was applied with pre-plant and side-dressing applications (Online Resource 1). Weed control was provided by spring tine harrowing (Series 982, Type 3, Lely Industries NV, Maasland, Holland) on June 15; inter-row cultivations (Model 183, Case IH, Racine, WI) on June 15, June 25, and July 7; and disc hillings (Weedmaster, Elomestari Oy, Ltd., Kukkola, Finland) on June 25 and July 10. Yield was defined as the fresh mass of ears from both first and second harvests, occurring August 24 and September 2, respectively.

Economic analyses

Economic modeling was primarily based on annual revenue, labor expenses, and materials expenses obtained from our field experiments. Additionally, assumptions of crop price, fuel usage, and fixed costs were estimated (Online Resource 3) in accordance with Lazarus (2015). The buildings and equipment were estimated based on the average size of an organic vegetable operation in ME, USA, which is 1.42 ha (USDA NASS 2014). Annual revenue was determined by multiplying the wholesale crop price by the marketable yield.

The amount of labor required for planting, weeding, mulching, and harvesting was recorded to the nearest second with stopwatches. Labor required for other tasks was estimated (Online Resource 3). Evenness of labor over the season was evaluated with Pielou's evenness index (J') (Pielou 1975), which was calculated by separating labor for each system into 2-week bins and using the following equation:

$$J' = \sum \mathrm{p_i} \ln \mathrm{p_i} / \ln(S) \quad (1)$$

where p_i is the proportion of labor in each bin and S is the number of bins (10).

Expenses of all purchased materials were logged. Return over variable costs (ROVC) was calculated as the annual revenue minus related operating costs such as labor, fuel, seedlings, and fertilizer. Net farm income (NFI) was calculated as the annual revenue minus both the operating costs and the ownership costs such as depreciation on equipment, fixed cost of land, and taxes and insurance on fixed capital.

Economic risk and sensitivity analyses were performed using @RISK (Palisade Corporation, Ithica, NY) following Özkan et al. (2015). The @Risk software was used to define the distributions of several key input variables (Online Resource 3) within our Excel (Microsoft Corporation, Redmond, WA) budget model for each weed management system. Using @Risk, 1000 Monte Carlo iterations were run, in which values of input variables were randomly selected from predefined distributions. The input variables included fuel price, wage rate, hay price, onion yield, onion price, and labor required for planting, weeding, mulching, and harvesting. Economic risk was evaluated using the resulting cumulative distribution function (CDF) curves, which display the probability of achieving an NFI less than or equal to x. Evaluation of the differences between CDF curves were used to determine riskiness and stochastic dominance among the different systems (Hardaker et al. 2004), where system A is first-order stochastically dominant to weeding system B if the CDF for A is entirely to the right of the CDF for B. However, if two CDF curves cross, second-order stochastic dominance is determined by the following:

$$\int_{-\infty}^{x^*} FA(x)dx \leq \int_{-\infty}^{x^*} FB(x)dx \quad (2)$$

where if the area under the CDF for weeding system A is less than the area under the CDF for weeding system B, then system A is preferred to system B from an economic risk perspective. Both first- and second-order stochastic dominance assume farmers are risk-averse. Even though system B may have a slightly higher NFI than system A, the lower variability of system A may be preferred (Hardaker et al. 2004).

For each weed management system, sensitivity analyses were conducted through tornado graphs, in which the high and low values of each input variable from the Monte Carlo simulation were used to graph high and low NFI as other variables were held constant.

Statistical analyses

Statistical analyses were completed in JMP 10 (SAS Institute Inc., Cary, NC). Effects of weed management systems on labor requirements were evaluated with ANOVA. With the exception of workload evenness, years were analyzed separately due to year by treatment interactions. Mean comparisons were conducted using Fisher's protected LSD. Data failing to meet assumptions were transformed as necessary or analyzed with the nonparametric Kruskal Wallis test (Kruskal and Wallis 1952) and pairwise Wilcoxon signed-rank test (Wilcoxon 1945). A contrast was used to compare planting labor between systems with bare soil and the PE mulch system. A significance level of 0.05 was used throughout the study. Analyses of NFI, risk, and sensitivity were conducted across study years to incorporate variability of each system.

Results

Onion production labor

Labor required to hand-transplant onions differed between plots with bare soil at the time of transplanting—critical period, zero seed rain, and hay mulch systems—and those with PE film ($F_{1,42} = 14.005$, $P < 0.001$); labor requirements were 366 (SE = 21) h ha^{-1} and 577 (SE = 11) h ha^{-1}, respectively. Weeding, mulching, and harvesting labor differed by weed management system (Table 1). On average, the zero seed rain system required 65% more weeding labor than the other systems. The zero seed rain system also had the most even workload (Table 1) reflecting the relatively constant weeding labor (Fig. 1), while the hay mulch system had the most uneven workload (Table 1) due to the concentrated mulching requirement (Fig. 1).

Economic analysis for onion production

Annual revenue of onion production was greatest in zero seed rain and hay mulch systems, but both had high labor costs (Table 2). Material expenses differed by mulch cost, which was 509 USD ha^{-1} for the PE mulch system and 3850 USD ha^{-1} for the hay mulch system (Online Resource 4). NFI was greatest for the zero seed rain system followed by hay mulch, PE mulch, and critical period systems, respectively (Table 2), representing a range of 14,078 USD ha^{-1}.

In risk analysis, the zero seed rain system demonstrated first-order stochastic dominance compared to the PE mulch and critical period systems (Fig. 2).

Table 1 Labor use (mean ± SE) in onion production in four weed management systems. Within each column, means followed by the same letter are not significantly different

Weed management system	Weeding[a] 2014	2015	Mulching[b] 2014	2015	Harvesting[a] 2014	2015	Workload evenness[a]
	100 h ha^{-1}						J'
Critical period	8.8 ± 0.5 b	12.4 ± 1.1 b	0.0 ± 0.0 c	0.0 ± 0.0 c	2.0 ± 0.1 a	0.9 ± 0.1 b	0.69 ± 0.02 b
Zero seed rain	13.7 ± 1.1 a	17.7 ± 1.2 a	0.0 ± 0.0 c	0.0 ± 0.0 c	1.0 ± 0.1 b	0.5 ± 0.1 c	0.86 ± 0.01 a
Polyethylene mulch	9.9 ± 1.4 b	10.8 ± 1.0 b	0.5 ± 0.0 b	0.3 ± 0.0 b	2.0 ± 0.3 a	1.2 ± 0.0 a	0.66 ± 0.02 b
Hay mulch	7.5 ± 0.6 b	7.7 ± 0.3 c	9.4 ± 1.0 a	6.9 ± 0.1 a	1.0 ± 0.1 b	0.8 ± 0.1 bc	0.59 ± 0.03 c
ANOVA	P						
System	0.004	< 0.001	< 0.001	< 0.001	0.002	0.002	< 0.001

[a] Means separated using Fisher's protected LSD at $P \leq 0.05$

[b] Main effects tests performed with Kruskal Wallis tests (Kruskal and Wallis 1952) and mean comparisons performed with Wilcoxon paired tests (Wilcoxon 1945), both at $P \leq 0.05$

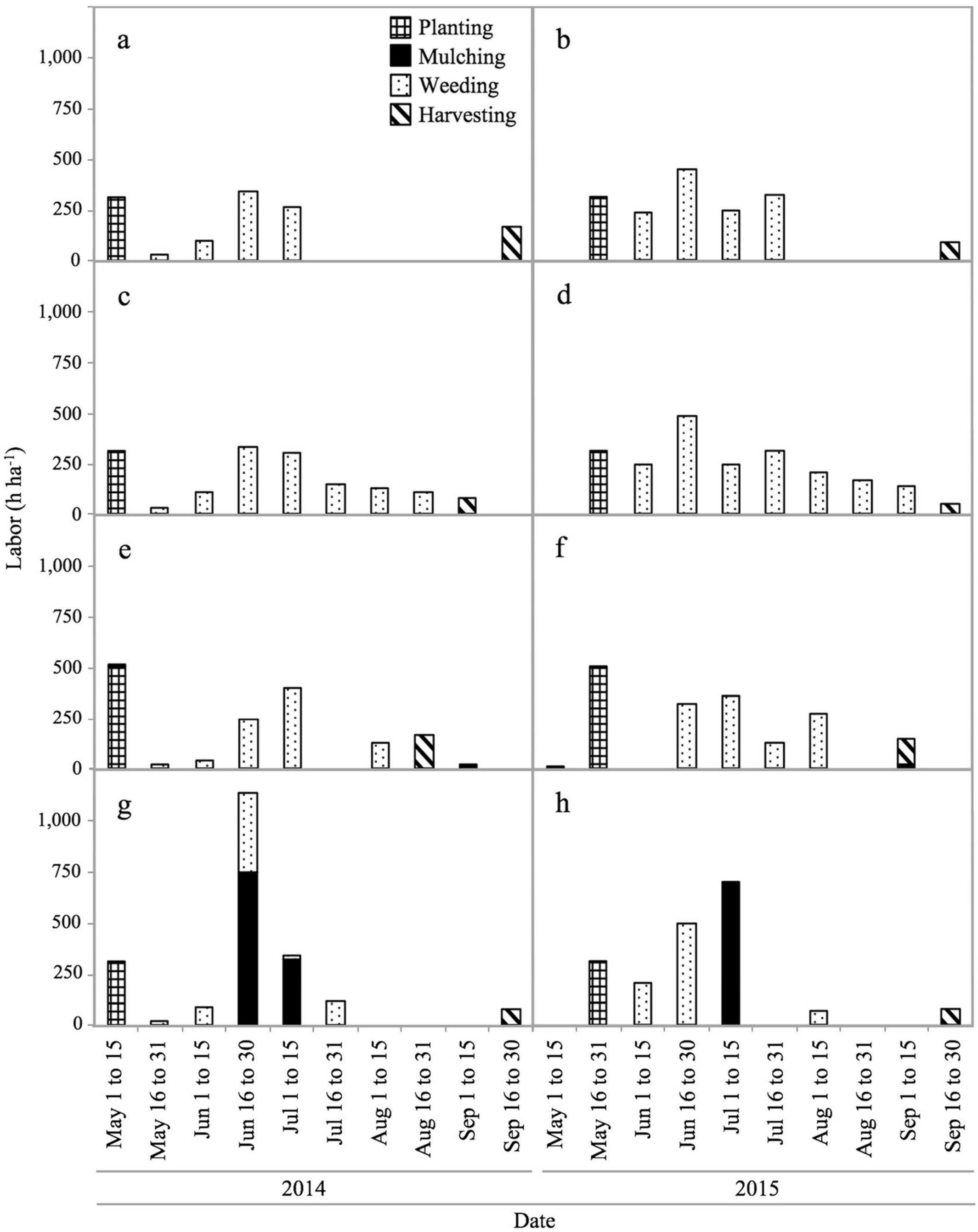

Fig. 1 Temporal spread of labor required to grow onions using each weed management system: critical period (a and b), zero seed rain (c and d), polyethylene mulch (e and f), and hay mulch (g and h). Patterns within bars represent planting (gridlines), mulching (solid fill), weeding (dotted), and harvesting (diagonal lines)

But the hay mulch system exhibited second-order stochastic dominance over the zero seed rain system and the PE mulch system showed second-order stochastic dominance over the critical period system.

The tornado graphs demonstrated that for most systems, NFI was most sensitive to onion yield, followed by onion price, and wage rate (Fig. 3). NFI was more sensitive to weeding and transplanting labor than harvesting labor in all systems.

Table 2 Summary of enterprise budgets for onion production in four weed management systems

Weed management system	Annual revenue	Labor costs	Materials and other operating costs	Annual ownership costs	Return over variable costs (ROVC)	Net farm income (NFI)
	100 USD ha^{-1}					
Critical period	522	154	149	117	219	102
Zero seed rain	703	194	149	117	360	243
Polyethylene mulch	604	178	154	118	272	154
Hay mulch	724	199	188	117	337	220

Effect on the subsequent crop

In sweet corn grown in rotation after the initial onion crop, abundant weed emergence in former critical period plots was the likely cause of a sweet corn yield loss in those plots (Brown and Gallandt 2017a). Enterprise budgets for sweet corn production showed that NFI of the critical period system was −2187 USD ha^{-1}, whereas the averaged NFI of the other systems was 337 USD ha^{-1} (Online Resource 5). Despite the incorporation of hay mulch the previous year, soil organic matter did not differ by strategy, nor did yields in weed-free subplots (Brown and Gallandt 2017a).

Discussion

Despite the long-term focus of the zero seed rain and hay mulch systems on the weed seedbank (Nordell and Nordell 2009; Brown and Gallandt 2017b) and soil health (Schonbeck and Evanylo 1998b), respectively, these systems were most profitable in this short-term study. Their profitability likely relates to their exceptional weed control (Brown and Gallandt 2017a) and onions being a weed-sensitive crop (Ware and McCollum 1975; Bond and Burston 1996). Indeed, the onions yielded greatest in these systems (Brown and Gallandt 2017a) and NFI was generally most sensitive to onion yield (Fig. 3). Similarly, in organic mixed-

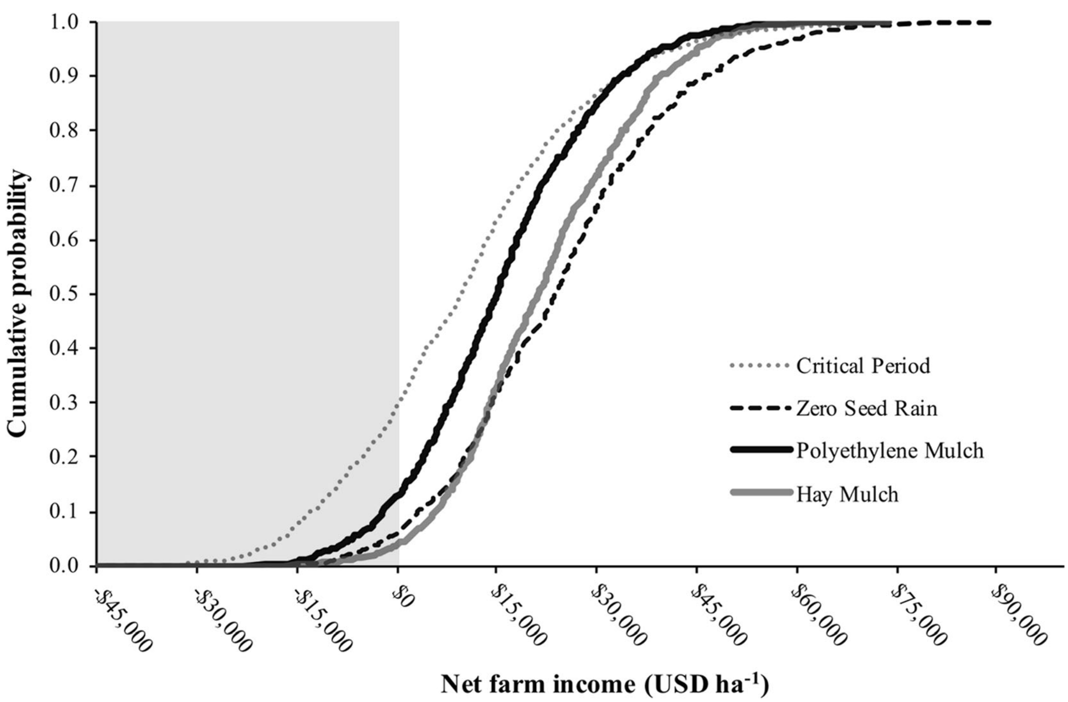

Fig. 2 Cumulative distribution functions of net farm income based on Monte Carlo simulation with 1000 iterations of each weed management system

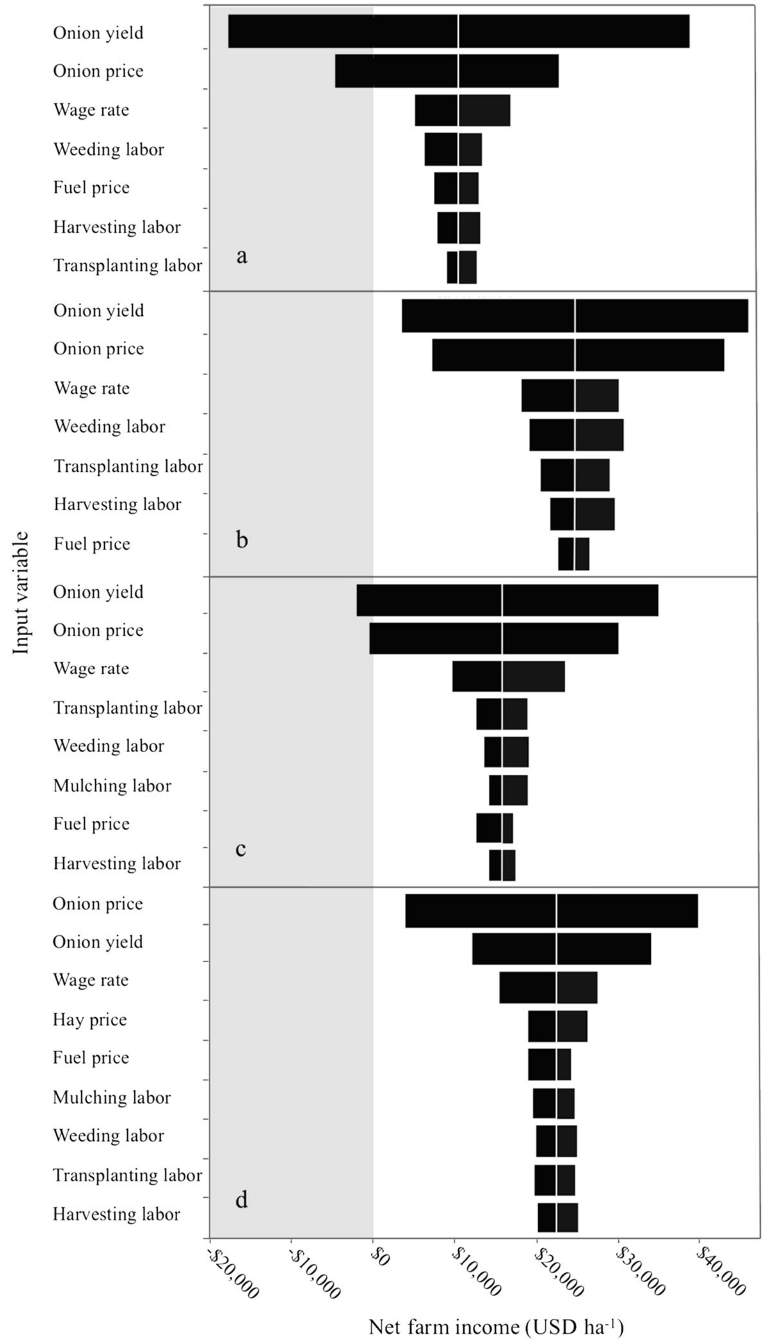

Fig. 3 Tornado graphs displaying the sensitivity of net farm income to variation in selected input variables for each weed management system: critical period (a), zero seed rain (b), polyethylene mulch (c), and hay mulch (d). Plotted net farm income was calculated by using the extreme values of 1000 Monte Carlo sampling iterations from each input variable, while all other variables remained at baseline levels

vegetable production, Chan et al. (2011) observed that yield was a more important determinant of profitability than input costs.

The zero seed rain system required the most weeding labor (Table 1), whereas the hay mulch system had the greatest total labor expenses (Table 2), consistent with the experience of farmers that have implemented these systems (Brown and Gallandt 2017b). The evenness of the workload in the zero seed rain system (Table 1) would perhaps be desirable for a farm with a steady but limited labor pool. A potential conflict of management priorities may arise in late summer, when the short photoperiod encourages many summer annual weeds to set seed quickly (Gifford and Stewart 1965; Weaver and

McWilliams 1980) but harvest operations also need to be conducted. Conversely, the uneven spread of labor in the hay mulch system would perhaps be best suited to farmers able to hire a short-term crew to complete the early-season mulching.

In the hay mulch system, NFI was sensitive to hay price (Fig. 3), reflecting the variability of this input. Hay may be procured for free in the case of spoiled, mulch hay or bought for as much as 0.28 USD kg^{-1} (Online Resource 3). Law et al. (2006) found similar sensitivity to price of natural mulches in bell pepper production; when mulch was obtained for free, profitability was similar to conventional production, but profitability was greatly decreased when mulches were purchased. As an alternative, in ME, USA, municipal leaf collections are used as an inexpensive mulch (T. Roberts, personal communication).

The PE mulch system did not perform favorably. It was unexpected that onion yield did not increase in PE mulch, since many crops (Kaya et al. 2005; Zhang et al. 2007; Trdan et al. 2008), including onions (Vavrina and Roka 2000), have shown a positive yield response. Yield loss in 2014 was likely due to warmer soil causing early senescence (Brown and Gallandt 2017a).

The increased transplanting labor in the PE mulch system and the added task of PE film removal were noted by Schonbeck (1998) to negate any labor savings compared to a hay mulch system. However, some small-scale growers have invested in water-wheel transplanters (Rain-Flo Irrigation, East Earl, PA) and PE film removal equipment (CropCare, Lititz, PA), which can increase the speed of operations (J. Kafka, personal communication). The weeding labor for the PE mulch system (Table 1) could perhaps be reduced by using smaller planting slits, but this would likely have increased transplanting labor (M. Guzzi, personal communication). Perhaps in more widely spaced heat-loving crops, black PE film would provide less opportunity for weeds to emerge through planting holes.

Despite the unfavorable performance of the critical period system (Table 2), it is commonly used by farmers (Jabbour et al. 2014), highlighting their keen interest in reducing labor costs. Indeed, the weeding labor reduction provided by a critical period approach offers a "huge, practical benefit" according to one farmer (M. Guzzi, personal communication). Additionally, in more weed competitive crops, the duration of the critical weed-free period is shorter (Knezevic et al. 2002), thereby offering more labor savings than in onions. However, one of the most important ecological effects of the critical period system was the abundant weed seed rain, which resulted in increased weed competition (Brown and Gallandt 2017a) and reduced profitability in the subsequent sweet corn crop (Online Resource 5). Therefore, thresholds for determining the level of necessary weed control based solely on yield of the current crop may not be advantageous (Norris 1999).

Conclusion

It is not our aim that farmers adopt a single "best" approach, but for farmers to understand the benefits and risks of each weeding system so that each may be used appropriately. Our research demonstrated that in the context of small-scale organic onion production, the more intensive systems—zero seed rain and hay mulch—performed favorably (Table 2). However, the critical period system may be preferable when in-season labor cost reductions are necessary (Table 2) and PE mulch may be preferable when early harvest is desired (Fig. 1).

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